PHYSIOLOGICAL CHANGES UNDER WORK STRESS AND ITS MEASUREMENTS THROUGH A FORCE PLATFORM

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JULY, 1982

Dedicated

to

my beloved wife

"MANORAMA"

CERTIFICATE

This is to certify that this thesis entitled "Physiological Changes Under Work Stress and its Measurements Through a Force Plateform" submitted in partial fulfilment of the requirements for the Degree of Master of Technology by Mr. Bishwa Mohan Sinha is a record of work done under my supervision and has not been submitted elsewhere for a degree.

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B.M. Sinha

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYNOPSIS

There are many real life situations where manual work is required for the accomplishment of a task. The physiological cost of performing the task is influenced by many factors such as nature of the task, environmental conditions, sex, posture and physical condition of the subject. The rate of energy expenditure is generally measured in terms of K.Cal per minute. Basically, the methods of measurement of physiological cost can be put in two categories. The first cetegory known as Direct Method of measuring physiological costs, includes either the measurement of CO_2 produced or the amount of oxygen consumed while performing a task. The other cetegory includes the measurement of physiological cost in terms of parameters like heart rate, breathing rate, pulse rate, sweating rate and the bodily reactions. However, the measurement of physiological cost in terms of bodily reactions offers certain distinct advantages over the other indirect methods since the worker can perform the task in a natural environment without being hampered by face mask, hoses, wires etc. The bodily reactions can be measured with the help of a force platform.

The objective of the present work is to study the effect of environmental parameters like temperature on the physiological cost of performing a selected task and to establish relationship for increase in heart rate with bodily reactions.

A manual task which involved lifting of weight was selected for the present study. The motivation behind the selection of this task was because such a task is encountered frequently in day to day life as well as in industrial situations. An ECG equipment manufactured by Electronic Corporation of India (ECIL) was used for measuring heart rate. A compact and portable force platform was designed and fabricated for measuring the bodily reactions. The designed force platform can measure forces in all the three planes namely vertical, lateral and transverse. The study involved measurement of heart rate and bodily reactions for four levels of lift height, three levels of temperature and four levels of exposure time. The experiment was carried out in an environmental chamber whose temperature could be controlled between 18° to $45\ ^{\circ}C$ ($\pm\ 2^{\circ}C$). Four healthy males in the age group of 18 to 25 years were used as subjects. The subjects were required to lift a load of 5 kg. with a frequency of 25 lifts per minute. Further, the subjects were required to maintain an included angle of 15° between feet while performing the task.

The experimental results suggested that the selected task of lifting of 5 kg. load can be classified as a moderately heavy physical task. The collected experimental data was statistically analysed. A multiple linear regression model was developed for increase in heart rate with resultant bodily reaction, lift height, temperature and exposure time. Within

the limits of present experimental design, it was concluded that for the selected task the increase in heart rate was significantly affected by the resultant bodily reaction and parameters like temperature, lift and exposure time did not have significant effect on heart rate.

INTRODUCTION

Every system whether a man made or biological system has got certain capacity and capability to perform task. At the time of designing a new machine, precise information about materials, structure, power, capacities and the like are generally asked for. The fact that a human can do a certain job does not by any means indicate that the job was properly designed. Information about physical and mental capacity of human beings can be generated by a coglomerate of science called human factors/ergonomics. Ergonomics is a scientific study of the relationship between man and his working environment. By environment it does not necessarily mean only the ambient environment rather the various aspects of our lives and the physical environment in which we live in.

With the rapid development in science and technology, people have been busy in developing new environments which seek more and more 'compatability' with human being in terms of human comforts, safety, and efficiency. An environment - be it physical or otherwise, all the time produces stimuli. These are received by man's receptor organs, e.g. eyes, ear, nose, skin etc., processed and decision taken thereon by the brain and responded accordingly by receiver. The environment also in turn reacts back to these responses and this information is fed back to the human brain.

Man is an adaptive animal whose efficiency as well as his capacity can be considerably enhanced by suitably designing the man-machine system. The system should be designed in such a fashion that the operator performs the task with reasonable efficiency. Physical effort and mental strain should be controlled so that he is free to devote his attention to those factors in his work where his judgement and flexibility, which he alone posses, can be used to greatest advantage. This would result in increased efficiency and effectiveness of the man-machine environment system.

Industrial situations involving biomechanical force are numerous and too complex to simulate in laboratories. Biomechanical energy sources in the form of human working capabilities are too extensively employed and need no elaboration, however, the measurement of work load and fatiguing stress are the problems which have been of great concern to the physiologists, psychologists and human factor engineers since long. Due attention needs to be paid to make the human tasks compatable and less fatiguing with the sole objective of higher productivity with most satisfactory working condition. For such studies an effective measuring system to record the effects of work stressors under real life situation is the most demanding requirement.

In an attempt to measure the effect of performing a task, the energy expended by an operator has to be found out. The energy which an operator expends while he performs is a purely physical phenomenon and is influenced by factors like fatigue, effort, monotony and job satisfaction. The rate of energy expenditure is generally measured in terms of calories per minute, which is generally found out by measuring physiological changes. Basically there are two methods for the measurement of physiological cost which are described below.

The direct method of measuring physiological cost involves measurement of carbon dioxide produced by work. The carbon dioxide expelled during and for a short while immediately following the work period is directly proportional to the energy expended. A variation of this method employs a pure oxygen supply which is inhaled by the worker while under test. The amount of oxygen consumed gives the basis for direct computation of energy spent.

The indirect methods of finding out the physiological cost involve measurements of heart beat, breathing rate, pulse rate, sweating rate etc.

For the performance evaluation of composite man-machine environment system, heart rate measurement technique can be used advantageously. It is also useful in assessing physiological demands while at work. It also

helps in finding out energy cost for different physical activities. Heart rate is reasonably indicative of the effects of heat stress and emotional stress. However, it is also related to individual factors like constitution, structure, physical condition, sex etc. of the subject.

Each individuals behaves independently in imparting human body reaction while performing a physical task according to the manner, the body structure and posture adopted to suit his own convenience. The bodily reactions can be measured with the help of a Force Platform. Like the measuring of heart rate, measurement of bodily reactions also provides an indirect method for assessing the physiological changes. The measurement of bodily reactions offers certain advantages over the heart rate measurement method since the worker can perform the task in a natural environment without being hampered by face masks, hoses, wires and all other usual paraphernellia. The force-time recording can be used as an indicator of energy expenditure and is nearly as accurate as metabolic measurements or heart rate measurements.

Force Platform

A Force Platform is a small compact platform on which a subject stands when carrying out some physical activity. By the use of some sensing element below the platform it is possible to sense and then automatically record the reactions imparted by the subject in each of

the three planes, namely, vertical, lateral and transverse. With the help of suitable sensors, the device can be made very sensitive to detect slight differences in physical movements. Further, the three dimensional forces for different activities can be measured and compared.

SCOPE OF THE PRESENT WORK

As pointed out earlier the physiological cost can be measured both in terms of heart rate and the bodily reactions imparted by the subject while performing a task. The objective of the study is to establish whether there exists a relationship between the two types of measurements or not. For this purpose a suitable manual task which involved lifting of weight was considered suitable because such a task is encountered frequently in industrial situations, construction work and various day to day activities. The heart rate measurements were carried out with the ECG equipment manufactured by Electronics Corporation of India. For the measurement of bodily reactions a Force Platform was designed, fabricated and calibrated. The study involved measurement of heart rate and bodily reactions for four levels of lift height, three levels of temperature and four levels of exposure time. The experiments were performed under controlled environmental conditions for which an environmental chamber was used. The experiments were carried out on four healthy male subjects in the age group

of 18 - 25 years. The collected experimental data has been statistically analysed. A multiple linear regression model has been attempted between increase in heart rate and bodily reactions, temperature, lift height and exposure time.

Chapter II has been devoted to literature review concerning measurement of bodily reactions using Force Platform, physiological cost of performing various types of real life tasks including load lifting task.

Chapter III deals with the experimental set-up. A brief description of the designed and fabricated Force Platform is given. This chapter also deals with the task design and the experimental design. Details of instrumentation required for conducting the experimental investigation are also dealt in this chapter.

Chapter IV deals with the data collection and the experimental procedure followed. The data has been statistically analysed for drawing inferences.

Chapter V gives conclusions of the experimental investigation and scope for further investigations.

CHAPTER 2

LITERATURE REVIEW

A brief review of the literature on measurement of bodily reactions using Force Platform is presented herewith.

2.1 FORCE PLATFORM

The first evidence of involving the use of force platform for studying the physiological measurements appears to be by Lauru [15, 16] in 1949. He called his platform "Effort detector" and used piezo-electric quartz as the sensing device. It was observed that the performance characteristics of piezo-electric transducer are influenced by temperature humidity and the oscillatory nature of forces experienced while performing manual tasks. Moreover, frigility of piezo-electric transducers make them less suitable as sensing device in force platform. Subsequently, Ismail, Barany and Manning [14] , Greene and Morris [9, 10] Greene, Morris and Wiebers [11] developed force platform using Linear Variable Differential Transformer (LVDT) as sensing device. Since LVDT's are also temperature sensitive as well as expensive, electrical resistance gauge was considered to be a promising sensing device. Varshney [26] developed a force platform using strain gauges.

The present thesis is a study on human performance and physiological changes which occur during repetitive

lifting of load under varying environmental conditions. Therefore a review of the literature available on the subject matter is presented.

2.2 PHYSIOLOGICAL COST OF PERFORMING MANUAL TASK

In 1956 Young [30] investigated the human heart rate recovery as a measure of human work. The task consisted of operating a small hydraulic pump in a closed fluid system. 14 male graduates, between the ages of 23 - 31, served as operator in operating the handle of apparatus at a work pace of 80 - 120 double pump strokes per minute. The result of the study consisted of heart rate recovery curve for each operator, a composite or mean set of heart recovery curves, an analysis of variance for significance of the effect of pace upon heart rate, and the computation of correlation coefficients for pace upon heart rate. Brouha [4] and Edward and Amrine [7] claimed that when no satisfactory recovery can take place between a series of successive operations, the heart rate remains at high level for a progressively longer time during a recovery period indicating physiological fatigue.

Ekey and Hall [8], Greene, Morris and Wiebers [11] and Ingenohl [13] observed that oxygen consumption can be taken as one of the criterion to measure physiological changes during a physical activity.

Bink [3] has proposed the term physical working capacity to indicate the energy expenditure that can be maintained throughout the working time by an individual with given aerobic capacity (maximum level of oxygen intake). The study indicated that a normal healthy adult can work continuously at his aerobic capacity up to 21 kJ or 5 Kcal per minute without developing fatigue for an 8 - hr workday. Tomlinson and Manenica [25] suggested that an approximate physical index based on heart measurement can be useful and practical technique in the assessment of physiological demands of heavy work. Bell and Wright [1] conducted experiments on 44 students trainees for a variety of under water task. Energy expenditures were predicted from heart rate. The authors have developed linear equations which can be used to determine oxygen requirements for leg and arm task seperately.

Piemental and Pandolf [21] and Pandolf Givoni and Goldman[20] proposed a non-linear relationship between metabolic rate and body weight, external load, velocity, terrain and grade. Their model is useful for predicting physiological cost involved during standing or walking very slowly with load along a gradient. Wyndham, Strydom and Morrison [29] established a regression line relating oxygen consumption and rate of work. They claim that if the task is such that the body weight is not lifted against gravity,

then oxygen consumption of heavier man and lighter man will be similar. The former will be using less oxygen per kg of weight and operate at lower percentage of his maximal capacity.

Treadmill is used as a pace setting device for walking stress measurements. Treadmill experimentation technique was used by Malhotra and Ramaswamy [18] . Subjects were asked to walk with additional load on their back during the experiment. The results revealed that metabollic cost of carrying normal load is the same as carrying an equivalent amount of additional weight. Duncan, Gardener and Barnard [6] also used treadmill at a constant speed of 4 KMPH on a 10 percent grade for testing 11 trained fire fighters for 15 mins. The author claimed that the heart rate increased significantly in each trial and the starting heart rate also increased with increase in load carried by the fighters. Nag, Sen and Roy [19] carried out tests on four workers who carried loads (no load, 60, 80 and 100 kg) at 0.89 and 1.03 m/s on a treadmill during the pre and post lunch period to obtain information regarding the degree of exhaustion from similar load carrying in their usual working situation. The rate of work is expressed in watts. During pre and post lunch work there was a rise of 6 to 71 of pulmonary ventilation with each increment of 163 W, beyond the initial work level. The oxygen consumption in the prelunch period were 15 to 27% higher, suggesting a greater

anaerobic metabolism in the post-lunch period. The average workers pulse-rate varied from 116 to 162 bpm. Cardiac demand for a particular load is more or less constant, irrespective of time of day. During the pre-lunch period the work-pulse sum was 78, 71, 65 and 54 beats per 163 W for respective four loads, where as in the post-lunch period, except the initial load, it varied only between 56 to 60 beats per 163 W, including a proportionate rise of pulse rate during post-lunch work. The 1st, 2nd and 3rd minute recovery pulses of the 3rd and 4th loads were much beyond a level estimating throughout the day. The recovery-pulse-sum varied from 39 to 104 beats and 36 to 117 beats/min. during the pre and post-lunch periods respectively, which were mostly beyond the permissible endurance limit. The oxygen consumption for similar loads were 18 to 44 percent higher in the pre-lunch period, indicating better ability to do work. To arrive at a reasonable load and rate of work, simple and multiple regression equations have been involved. The authors suggest that Indian workers may be allowed to work up to 1140 W (i.e. 50 to 55% of maximum oxygen uptake). Saha, Dutta, Banerjee and Narayana [23] conducted experiments on five physically active young healthy workers aged 20 - 24 years under comfortable working conditions to determine acceptance work load for sustained physical activity by asking them to run on a treadmill for 8 hours at different relative loads. Authors developed a relation between heart

rate and energy consumption and suggest that acceptable level of energy expenditure and heart rate could be taken approximately as 18 kJ per minute and 110 beats per minute. The relation is as follos:

$$\text{Heart rate} = 2.40\ (\text{Energy expenditure in kJ/min}) + 66\ \text{beats/min.}$$

Bicycle ergometer is another device for pace setting. Hueting and Sarphati [27] conducted experiments on 8 subjects in the age group 19 years to 23 years. The subjects performed exercise on a bicycle ergometer. Experimental set-up was such that the subjects were unaware of changes in the external milieu, that is, the variation in height of work load or whatever other external cue. Authors found significant correlationship between fatigue, physiological variables and load level. Verma, Malhotra and Sengupta [27] performed experiments on 55 subjects to establish a multiple linear equation for estimating energy expenditure from minute ventilation and heart rate during various grades of submaximal work on a bicycle ergometer. Westerling and Kilborn [28] studied four male employees engaged in the task of distributing gas cylinders. Occupational activities consisted of truck driving with frequent stops for loading, unloading and dragging cylinders. From the experimental results authors concluded that the distribution of gas cylinders is characterised by a low to

moderate average strain with frequent occasions where very great demands are made on the cardiovascular system as well as on muscular activity.

Sengupta, Sarkar, Mukhopadhyay and Goswami [24] performed extensive experiments on 15 male subjects, who were asked to perform cycling task of various intensities at three temperature levels. The authors have proposed linear regression relationships between energy expenditure and pulse rate for each temperature level. Seperate regression equations are established for pulse rates above and below 95 beats/min. Bashir, El-Sabagh and El-Nawawi [2] studied the effect of ambient temperature on the performance of male students (aged 20 to 23 years) under two work/rest ratios, they observed that the groups performance which was homogeneous at 20°C became heterogeneous performance when the working temperature was raised to 26 °C and 30 °C.

2.3 PHYSIOLOGICAL CHANGES DURING LOAD LIFTING

Lifting of load is a phenomenon which occurs quite frequently in real life situations. This type of stressing situation and the physiological cost associated with it has been studied by Legg and Myles [17]. Ten soldiers were asked to lift and lower their selected load for an 8 - hour work-day. The authors observed that the average heart rate was 92 beats per minute and the subjects did not show any

evidence of cardiovascular metabolic or subjective fatigue. Ronnholm's [22] experiment was to investigate the effect while lifting with rythm and interruptions. He reported that lifting performed with a certain rhythm was much more economical than performed with interruptions. Experimental investigations carried out by Davies [5] suggest that the energy cost is influenced by both the range of lifting and work pace. Energy cost of lifting objects from the floor to about 20 inch is about half the energy cost of lifting the same weight from 20 to 40 inches.

CHAPTER 3

EXPERIMENTAL SET - UP

The objective of the present study is to investigate into the physiological changes which occur during repetitive lifting of load. While performing a task the subject exerts reactions in various directions (planes). The reactions can be measured with the help of a Force-Platform. Therefore, a Force Platform has been designed and fabricated as a part of the present work. A brief description of the Force Platform is presented in next section. Further details are provided regarding the instrumentation required for recording various forces. Static and dynamic calibration characteristics of the Force Platform are also investigated. This chapter also includes details regarding the task design, experimental design and the instrumentation required for measuring physiological changes in terms of heart rate.

3.1 FORCE PLATFORM

Many investigators have used cantilever supported platform structure for the measurement of body reactions. In the present design a spring supported floating system was adopted. Strain gauges were used to measure the reactions caused while performing a manual task by the subject on a Force Platform. The overall dimensions of the force platform were 1.4 m x 1.2 m x 0.3 m.

3.1.1 Structural Characteristics

The top of the platform, having equilateral triangular frame of 1 m size, was fabricated using 3 cm x 3 cm x 0.3 cm angle iron. Triangular pieces of 0.6 cm thick steel plate were welded from the bottom side to the corners of the top frame. A line sketch of the top of the platform is shown in Figure 1. Similarly the base, also of equilateral triangular shape of 1.2 m size, was fabricated using 5 cm x 3 cm x 0.3 cm angle iron. Trapezoidal and triangular pieces of 0.6 cm thick steel plates were welded at proper places to the corners of the base frame as shown in Fig. 2. To make the structure more sturdy and rigid, equilateral triangular sub-frame was welded. The top frame rested on the corners of double spring loaded bolts, which in turn rest on a cantilever beam (Figure 3(a)). The cantilever carried strain gauges as main sensing device to measure vertical reaction. The details of the vertical support are shown in (Figure 3(b)).

The spring loaded supports were used for bearing the vertical load and transferring the movement caused by reactions on the platform on to the cantilever sensors. For transverse movement two similar supports were used at either side of lateral axis to arrest the movement and transfer it to the sensors. Lateral axis carries one such support in the front and two in the rear. In all eight supports were used as shown in Fig. 4.

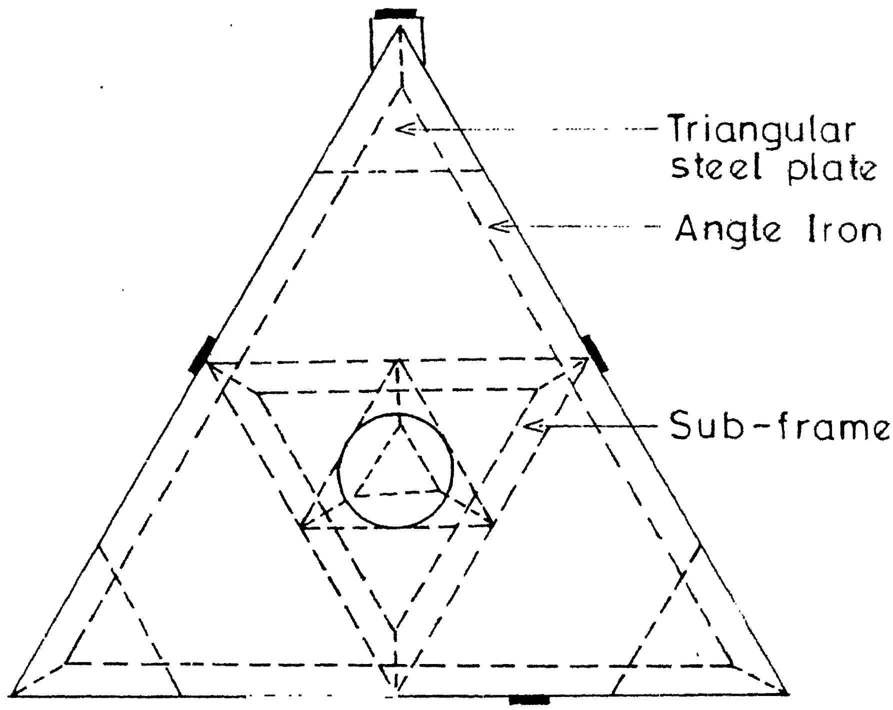
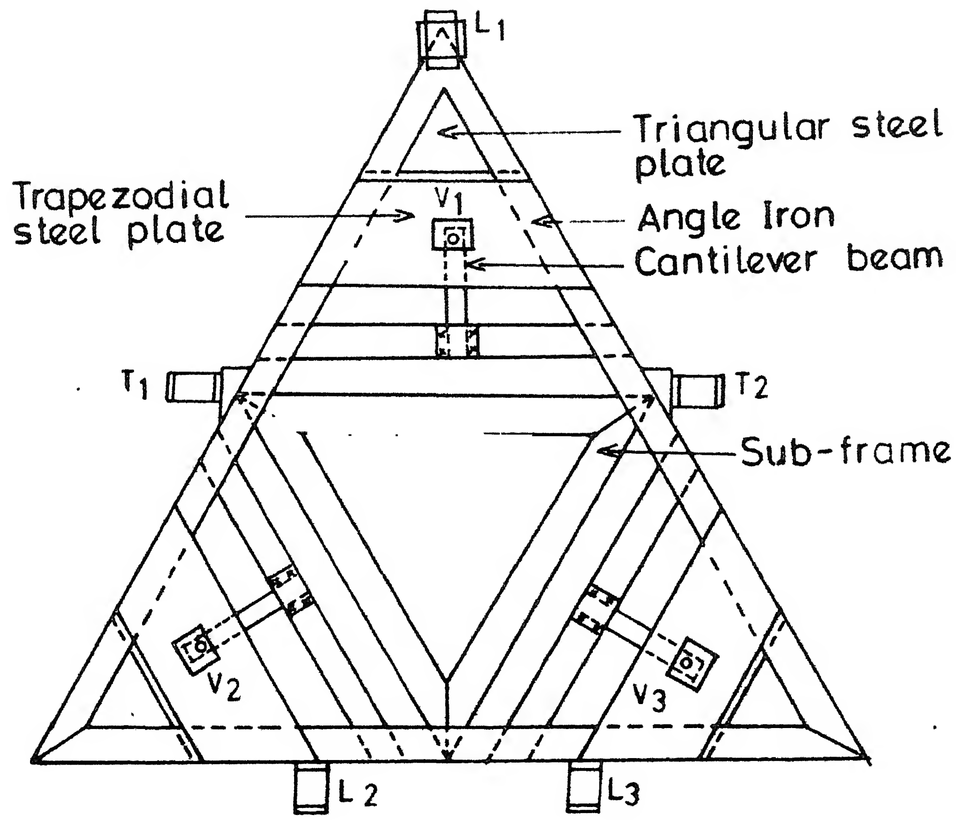


Fig. 1 Triangular top of plateform (Top-view)



V_1, V_2, V_3 - Vertical components of the reaction
L_1, L_2, L_3 - Lateral components of the reaction
T_1, T_2 -Transverse components of the reaction

Fig. 2 Triangular base of platefrom (Top-view)

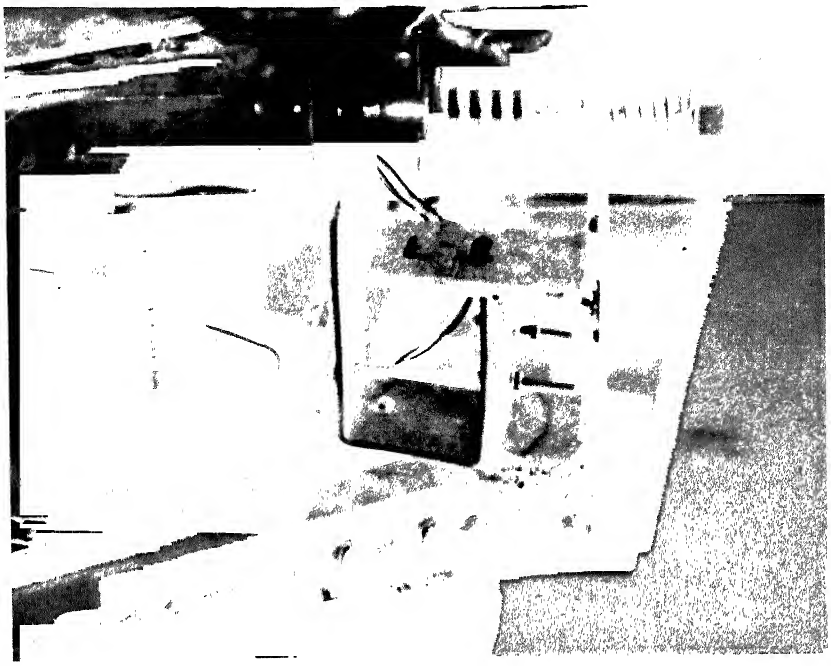


FIG. 3(a) : Top Frame Resting on Spring Loaded Bolt (Only one corner shown)

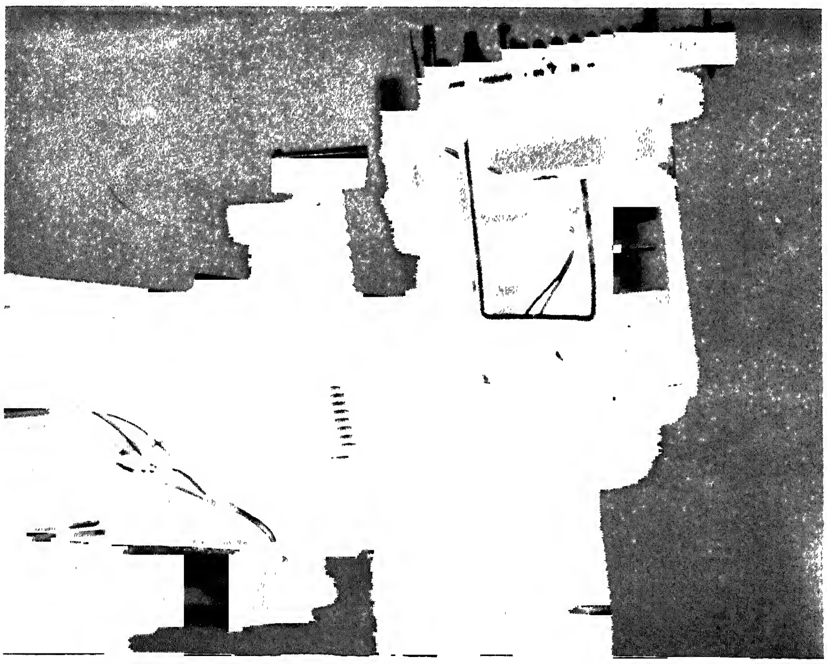


FIG. 3(b) : Details of Vertical Support

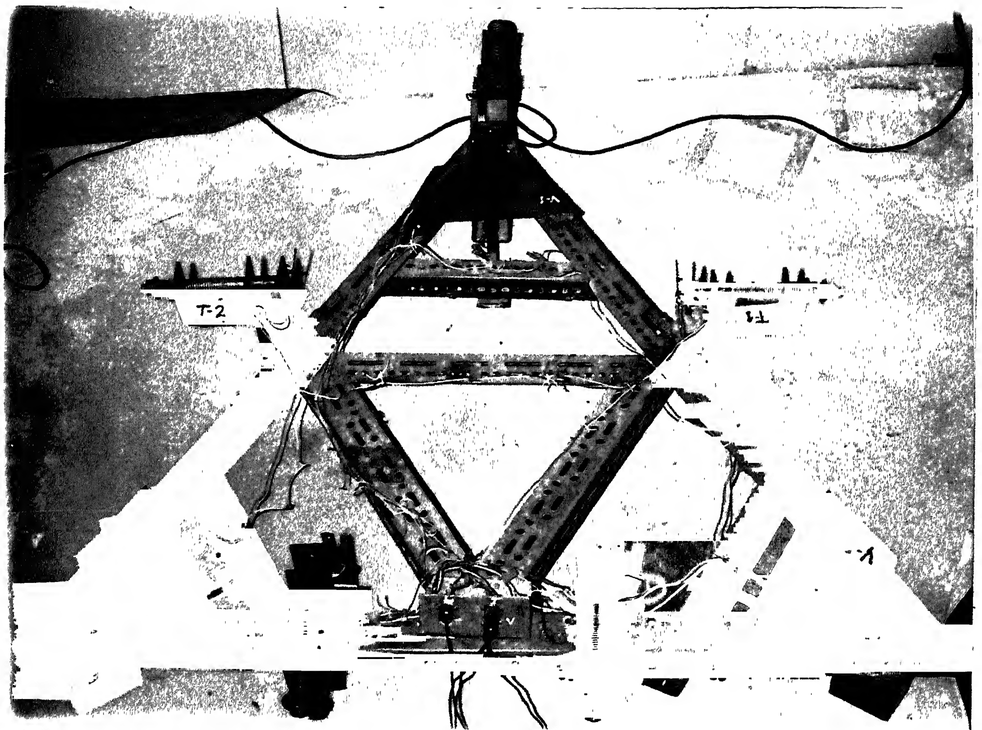


FIG. 4 : Details of Base of the Platform

Resistence strain gauges of 119.4 ohms, and gauge factor of 2.06 $\pm$ 2% were used for all the eight cantilever beams. One side of the cantilever beam carried the main sensing gauge whereas the other side carried the compensator gauge. All the main sensors undergoing similar loading strains were connected in series, i.e. strain gauges undergoing tensile strain due to the deflection of the beams were connected in series for one axis of deflection, whereas, strain gauges undergoing compressive strain for the same axis were separately connected in series. These two sets of strain gauges connected in series constitute two arms of the measuring device.

The transfer of movement from the main platform to the face plate of vertical support bolt, frontal and transverse arresters, was done through a point contact system. Steel balls of 8 mm size were used which provided an antifriction point contact with the main platform and the movements were taken by opposing springs mounted on the bolt. These springs provide floating type of adjustable contact between the two facing plates. The facing plates are separated by steel ball as shown in Fig. 5.

The pressure on contact balls was adjusted by tightening the float spring to obtain similar deflections in the sensing cantilevers. Through the proper tightening of spring it was ensured that the actual deflection of any

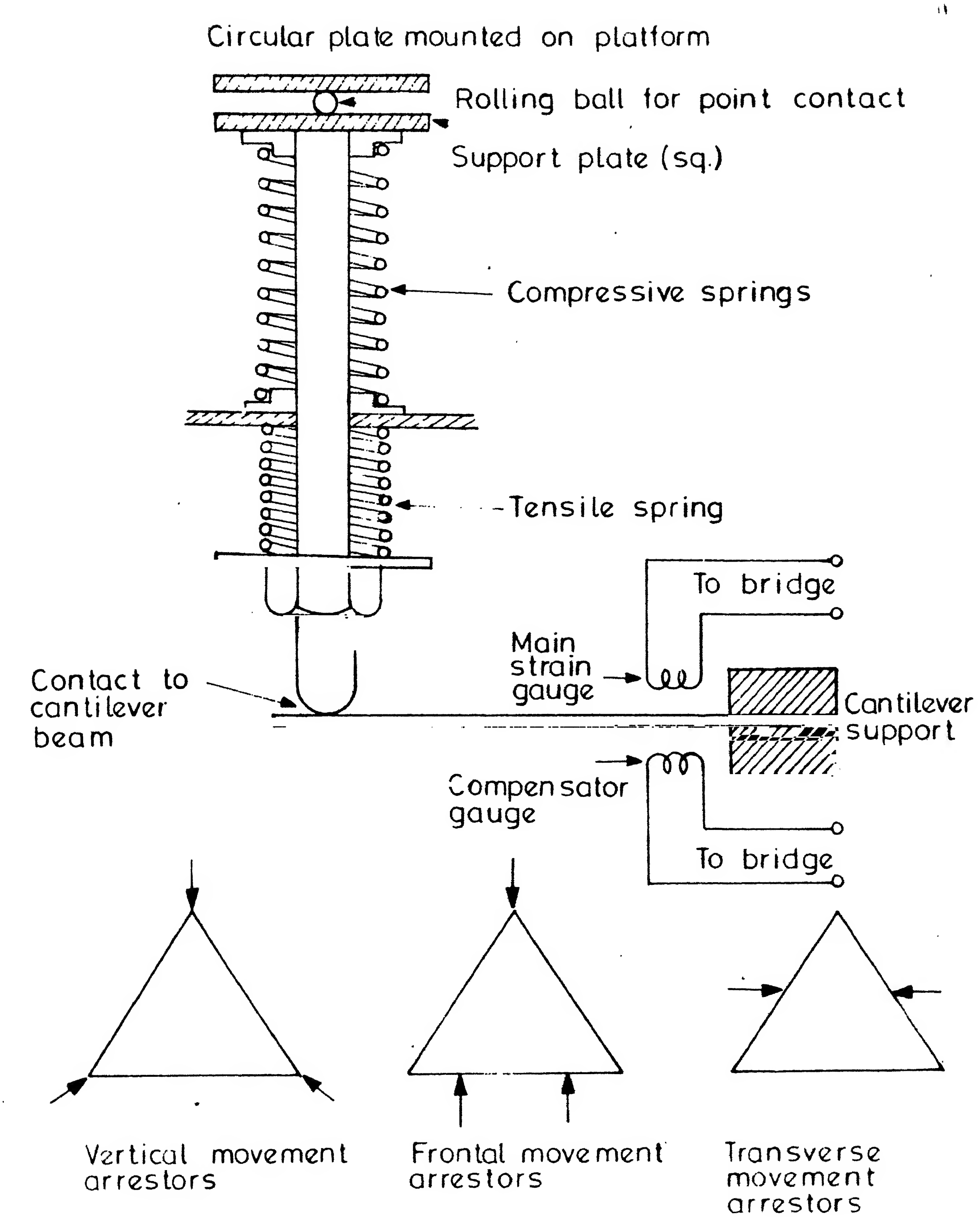


Fig. 5 Floating contact system

cantilever beam does not exceed 6 mm under the anticipated loads for performing the manual task on the platform. This restriction was imposed to avoid overstretching of strain gauges and to obtain linear characteristics.

The two facing plate surfaces were properly ground to give frictionless rolling contact to the balls. The facing plates were kept parallel to each other.

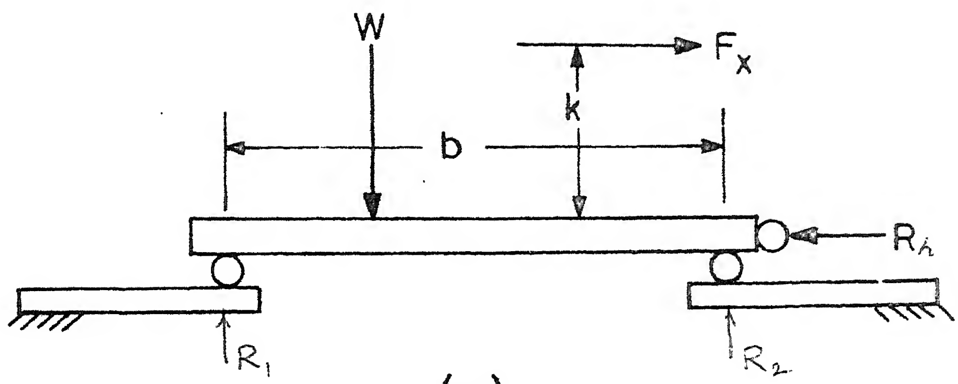
3.1.2 Theoretical Analysis

The following theoretical analysis was carried out to establish the effects of vertical and horizontal forces on the behaviour of the force platform.

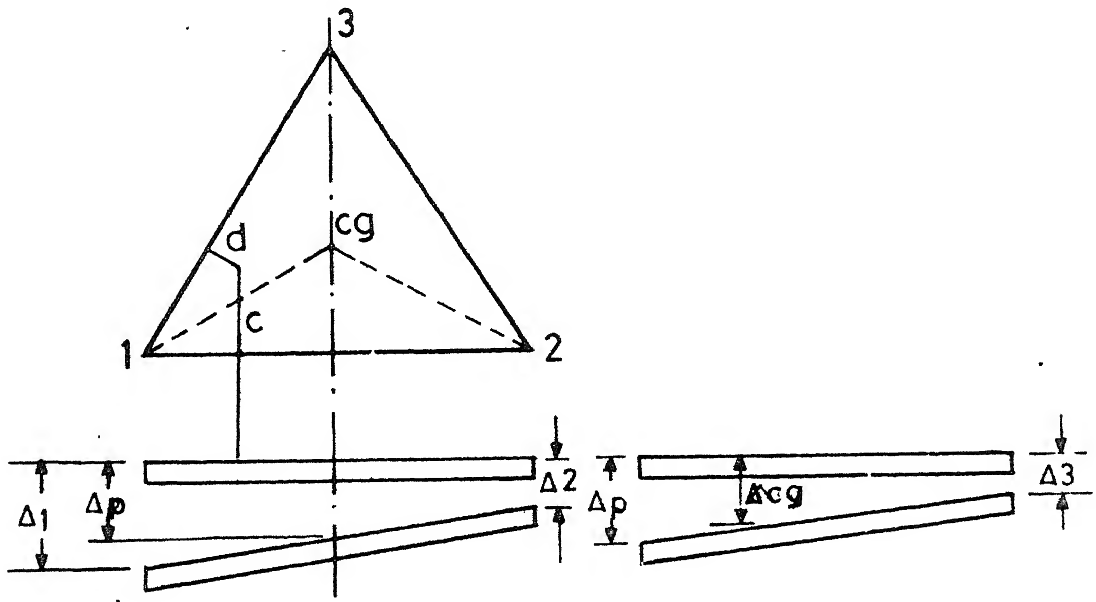
Vertical Forces:

As shown in Fig. 5, the platform has a round grounded plate at each corner which is free to move on a steel ball which is in turn free to move on the top of grounded square plate. The square plate is welded to a bolt, the lower end (semi-circular in shape) of which rests freely on the cantilever beam. Since the balls are free to move, they can not transmit any appreciable horizontal forces.

Simplyfying the explanation, Fig. 6(a) by placing the force, W, on a line between R_1 and R_2 and considering a simple beam the following expressions are obtained:



(a)



(b)

Fig. 6 Vertical force analysis

$$\Sigma F_y = 0 \qquad \Sigma F_x = 0$$

$$R_1 + R_2 - W = 0 \qquad F_x = R_h$$

This in itself is proof that R_1 and R_2 are uninfluenced by horizontal forces.

Therefore any force acting on this beam is vertical. It is important to show that in the proposed design, irrespective of the location of the vertical load within usable triangular area of the platform, the centre of the platform would experience the same vertical deflection.

Any weight, W as shown in Fig. 6(b), on the platform at a distance 'c' and 'd' from the two edges (1 - 2), (2 - 3), will deflect points 1 and 2 by the amount of Δ_1 and Δ_2. ΔP, midway between 1 and 2 will be deflected by

$$\Delta P = \frac{\Delta_1 + \Delta_2}{2}$$

Passing a section through P-3, it can be seen that the deflection of Cg by W is:

$$\Delta_{Cg} = \frac{2}{3}\left(\frac{\Delta_1 + \Delta_2}{2}\right) + \frac{1}{3}\Delta_3$$
$$= \frac{\Delta_1 + \Delta_2 + \Delta_3}{3}$$

Δ_1, Δ_2 and Δ_3 can be expressed as the function of the spring constant, k, and the reaction, R.

$$\Delta_1 = \frac{R_1}{k} \qquad \Delta_2 = \frac{R_2}{k} \qquad \Delta_3 = \frac{R_3}{k}$$

therefore $\Delta C_g = \frac{R_1 + R_2 + R_3}{3\,k} = \frac{W}{3\,k}$

so that it is shown that the deflection ΔCg is independent of any distance, d or c.

Horizontal Forces:

We need to show that the horizontal force beams situated as shown in Fig. 7 will be deflected only by the forces in the direction desired. The initial condition of the beams, meant for horizontal forces, is that they are preloaded. This is necessary so that as the load is transferred from the beam at one side of the platform to the beams at the other side a zero point will not be reached. Therefore, the beams must follow the motion at all times and the steel balls are retained by the residual pre-loading forces. Because of this initial condition, a state of equilibrium exists:

$$\Sigma F_x = 0 \qquad\qquad \Sigma F_y = 0$$

$$R_1 + R_2 = R_3 \qquad\qquad R_4 = R_5$$

For the sensing devices to give correct reading, it is essential for the platform to have a point of rotation at its centre M, which remains constant regardless of where a force, F, is applied. This becomes obvious in Fig. 7(a) as the force, F, is moved along the moment arm with a centre at M the value of R will change as 'a' and 'b' are altered.

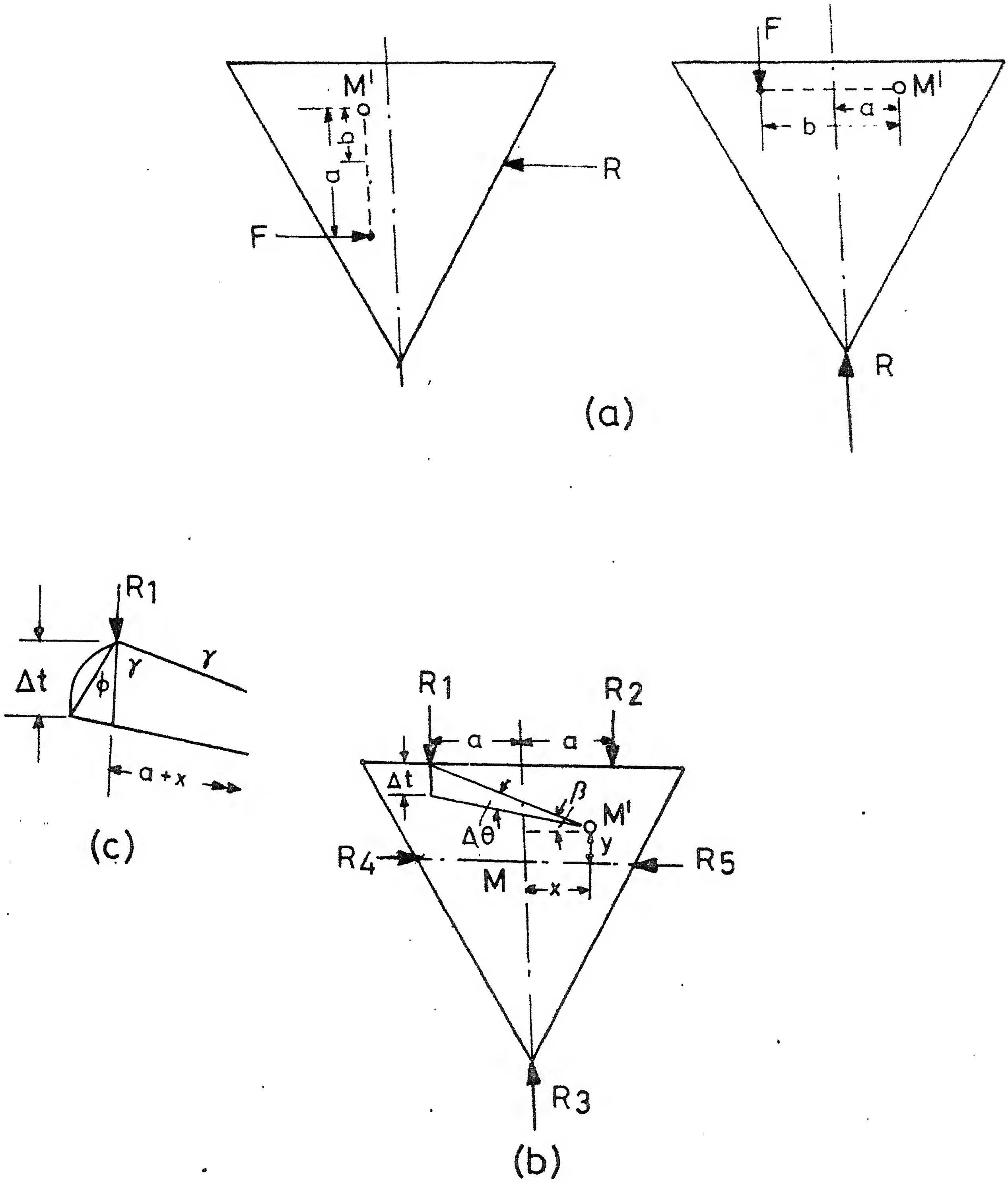


Fig. 7 Horizontal force analysis

Since forces on the platform (Fig. 5) are transmitted to the beam through the steel balls, only forces at right angles to the beams are sensed. However, it is necessary to prove that the platform rotates about M rather than any point, M'. The proof follows:

Assuming any point, M' Fig. 7(b), at position x and y from M about which the platform might rotate an angle $\Delta\theta$ radians

$$\frac{\Delta R_1}{\Delta t} = k_1$$

where k_1 is the spring constant of the beam.

Δt, can, for all purposes, be expressed in terms of radians and the radius since the length of the arc is nearly equal to the chord.

$$\Delta t = \Delta\theta \, (a + x)$$

From Fig. 7(c) :

$$j/r = \Delta\theta \text{ radians}$$

$$\therefore j = r \, \Delta\theta$$

$$\frac{\Delta t}{j} = \cos \phi$$

$$\phi = \beta \begin{cases} \phi + \gamma = 90^\circ \\ \beta + \gamma = 90^\circ \end{cases}$$

$$\Delta t = j \cos\beta$$

$$= j \, \frac{a + x}{r}$$

$$= \Delta\theta \, (a + x)$$

and it follows:

$$\Delta R_1 = \Delta\theta\ (a + x)\ k_1$$

Similarly

$$\Delta R_2 = \Delta\theta\ (a - x)\ k_2$$

$$\Delta R_3 = \Delta\theta\ x\ k_3$$

$$\Delta R_4 = \Delta\theta\ y\ k_4$$

$$\Delta R_5 = \Delta\theta\ y\ k_5$$

Proving that $y = 0$ it follows that for equilibrium:

$$\Sigma F_y = 0$$

therefore

$$\Delta R_4 + \Delta R_5 = 0$$

By substituting the values of R_4 and R_5 we get,

$$\Delta\theta\ y\ k_4 + \Delta\theta\ y\ k_5 = 0$$

$$y\ (k_4 + k_5)\ \Delta\theta = 0$$

Since the equation is equal to zero and the spring constant is same, y must be zero.

To prove that $x = 0$, it follows that for equilibrium

$$\Sigma F_x = 0$$

$$\Delta R_1 + \Delta R_2 + \Delta R_3 = 0$$

Substituting the values of R_1, R_2 and R_3 we get,

$$\Delta\theta \; (a + x) \, k_1 - (a - x) \, k_2 + x \, k_3 \;\; = \;\; 0$$

$$x = \frac{- a \; (k_1 - k_2)}{\Delta\theta \; (k_1 + k_2 + k_3)}$$

and since $k_1 = k_2$, it follows that

$$x = 0.$$

Therefore, the platform is only free to rotate about M, the centroid of the triangle.

From the results of above analysis, the conclusion is that any incorporation of the equilateral triangle would be valid for vertical suspension. Further, it is concluded that any symmetrical arrangement of horizontal restriction would satisfy the criterion for valid horizontal sensing.

3.1.3 Experimental Validation of the Platform

As depicted in Fig. 4, the vertical load is sensed by three cantilever beams. For the sensing of lateral and transverse loads the total number of cantilever beams involved are 3 and 2, respectively. It is important that for a given type of loading (vertical/lateral/transverse), each of the cantilever beams involved in sensing the static load experience the same amount of deflection. Mechanical adjustments of the spring were done to achieve this objective. Further, reproducibility in terms of the same amount of deflection for a given amount of load was checked through the repetitive static loading of the Force Platform. Lever

arrangement used for imparting lateral and transverse forces is shown in Figure 8.

Stability Test:

The leads of main and compensator resistence strain gauges from each of the three sets of cantilever sensors were connected to the three channels of the bridge balancing unit. The circuit of the bridge was energised by a 4.5 v DC power supply source. The three channels carried signals from cantilever sensors meant for sensing lateral, transverse and vertical loads. The balancing of the bridge was done by using a variac (potentiometer). Initially the output signal (from bridge balancing unit) was checked for null deflection on recorder for all the three channels separately. Loads of several values were applied in different directions and removed. In each case, it was found that upon the removal of loads the indicator came back to its original null position. This verifies the stability of the platform.

A test was conducted for different vertical starting loads. For this a number of subjects of different weights were asked to stand on the platform. The initial balancing of the bridge was done for null deflection on the recorder after the subject stood on the platform. Next the subject was asked to exert force by moving his body

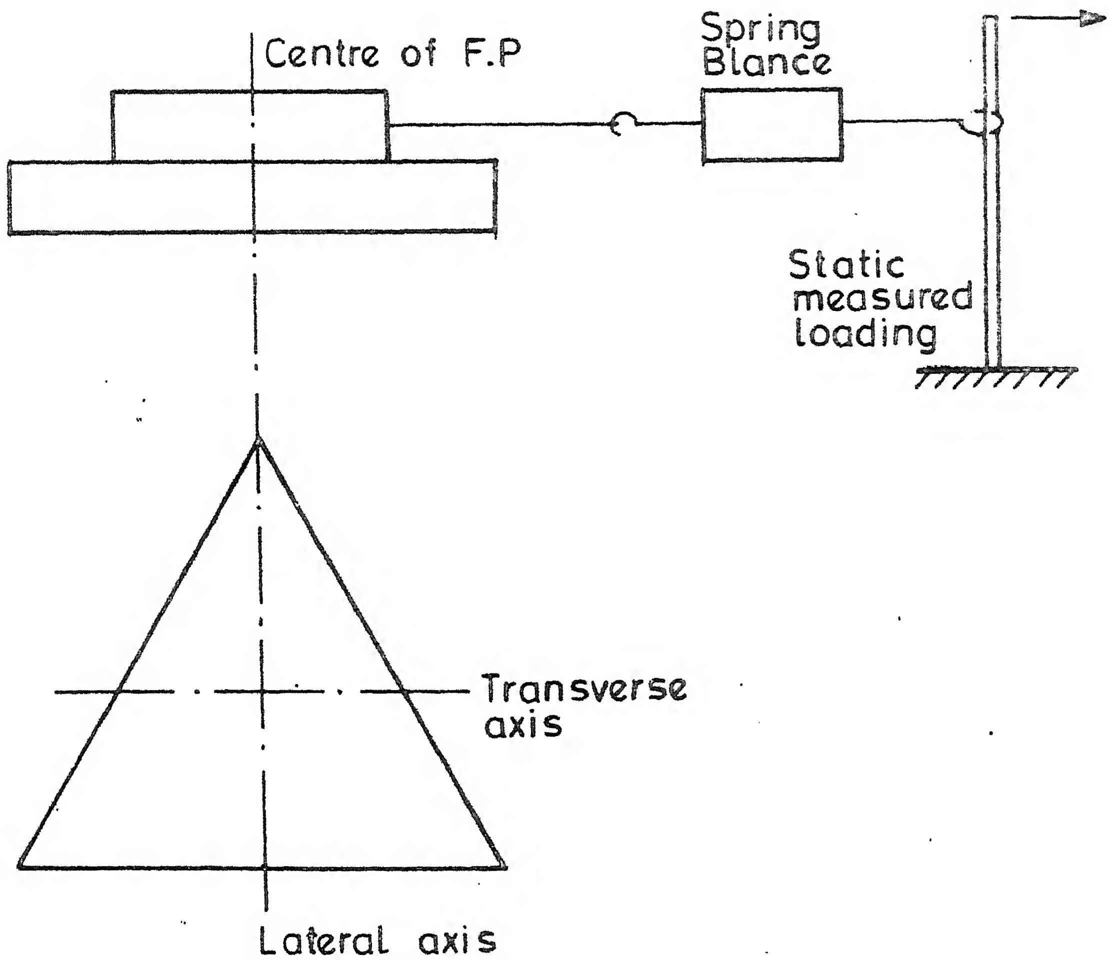


Fig. 8 Lever arrangement for imparting horizontal force

limbs and then come back to normal position. When the subject came back to normal position, it was found that the deflection on the recorder was zero. This further ensures the stability of the platform.

Static Calibration:

It was anticipated that for the weight lifting task selected for the present study, the forces exerted in either direction due to the performing of the task will not exceed 10 Kg. The details of the task design are given in section 3.2.

Keeping the average weight of the subjects in view, a weight of 50 Kg was placed on the platform. The bridge was balanced for null deflection on the recorder. Weights of 5 Kg, 10 Kg and 15 Kg were placed on the platform and the needle deflection on the recorder was noted. The procedure was repeated 5 times and average deflection for each load was determined. The plot of average recorded deflection vs vertical load is shown in Fig. 9.

Calibration plots for lateral and transverse loads were obtained for loads of 5 Kg, 10 Kg and 15 Kg using a lever and spring balance arrangement. Figures 10 and 11 respectively, give the calibration plots for lateral and transverse loads. The average deflection is based on 5 readings for each load.

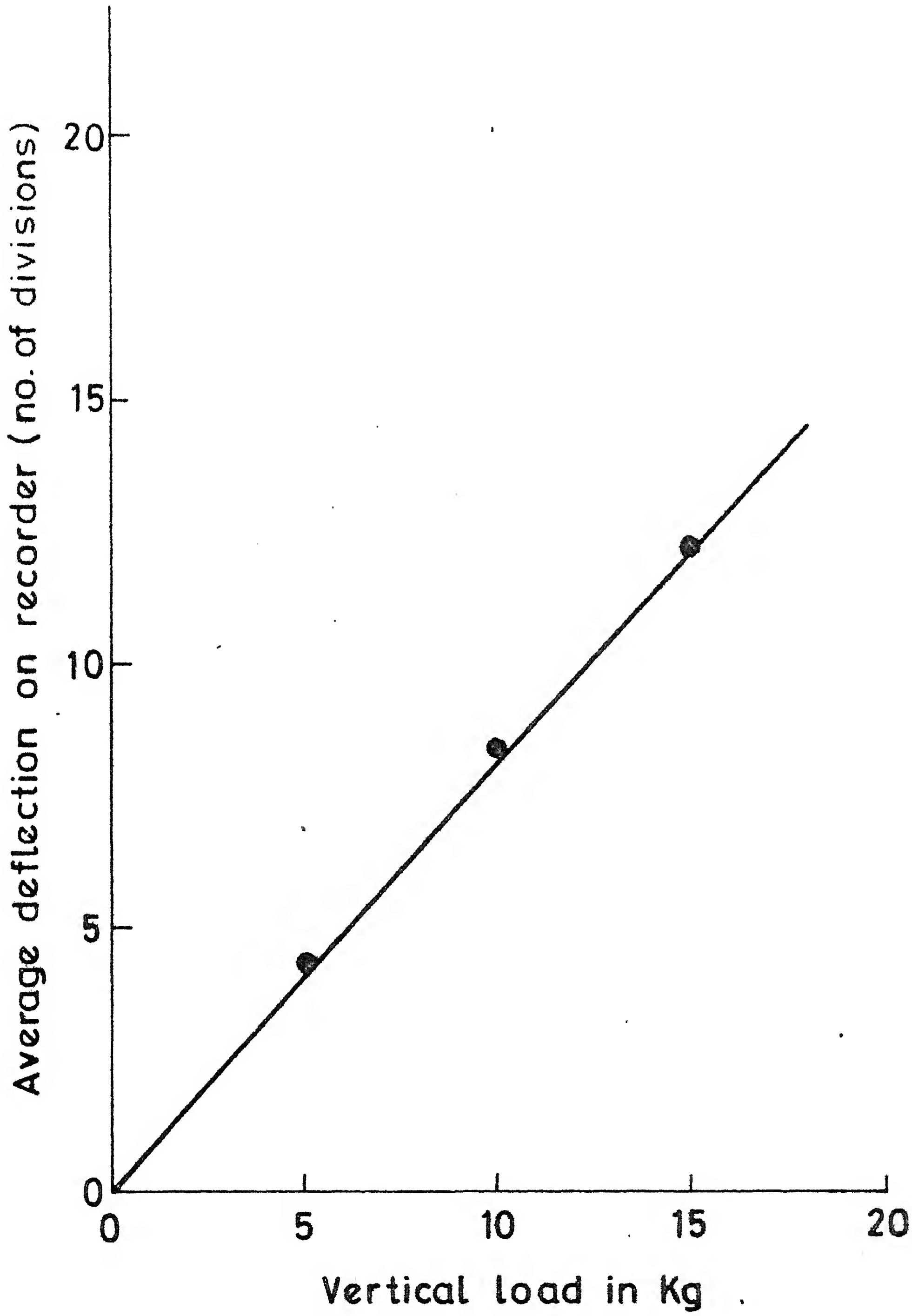


Fig. 9 Static calibration curve for vertical axis

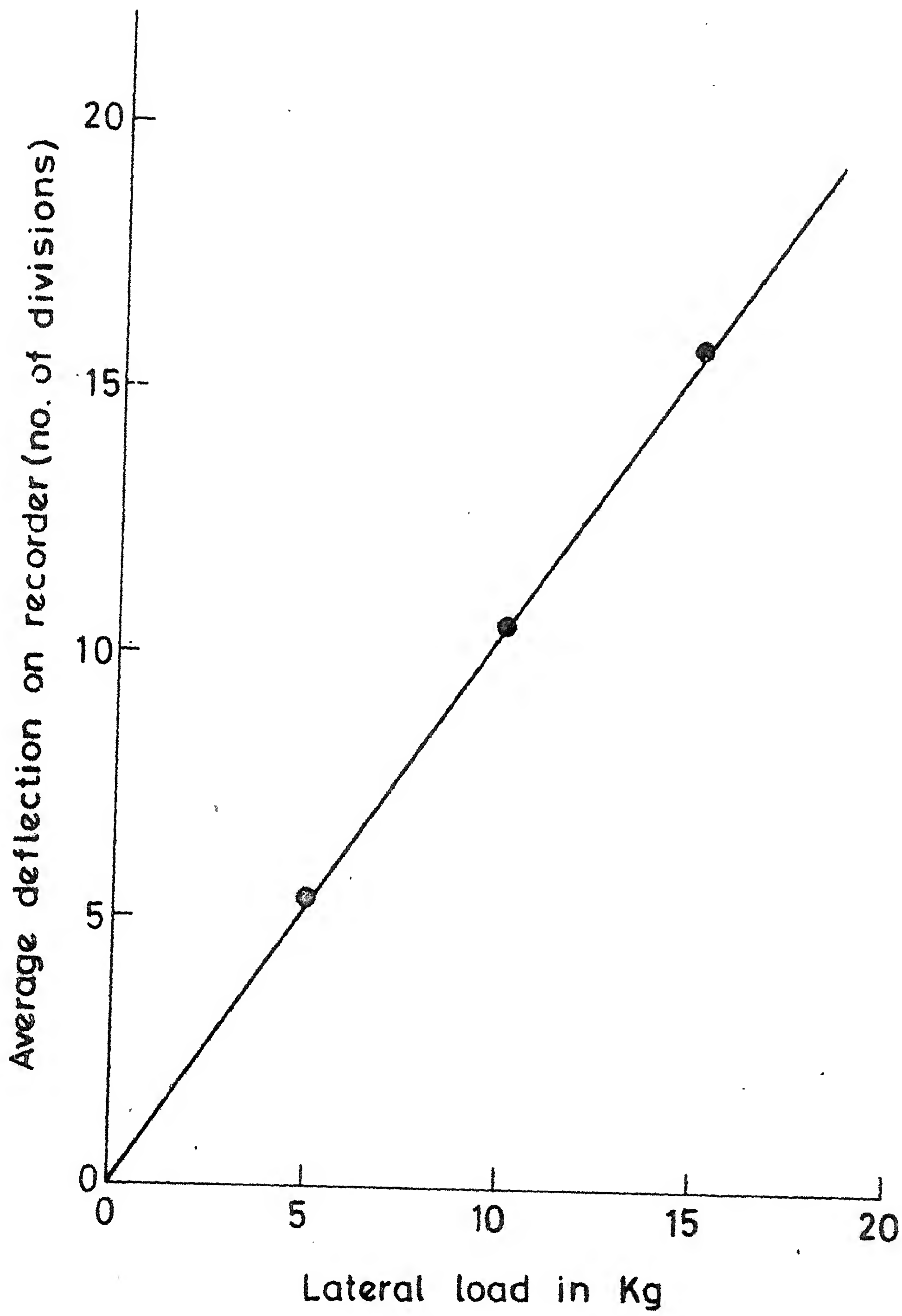


Fig. 10 Calibration curve for lateral axis

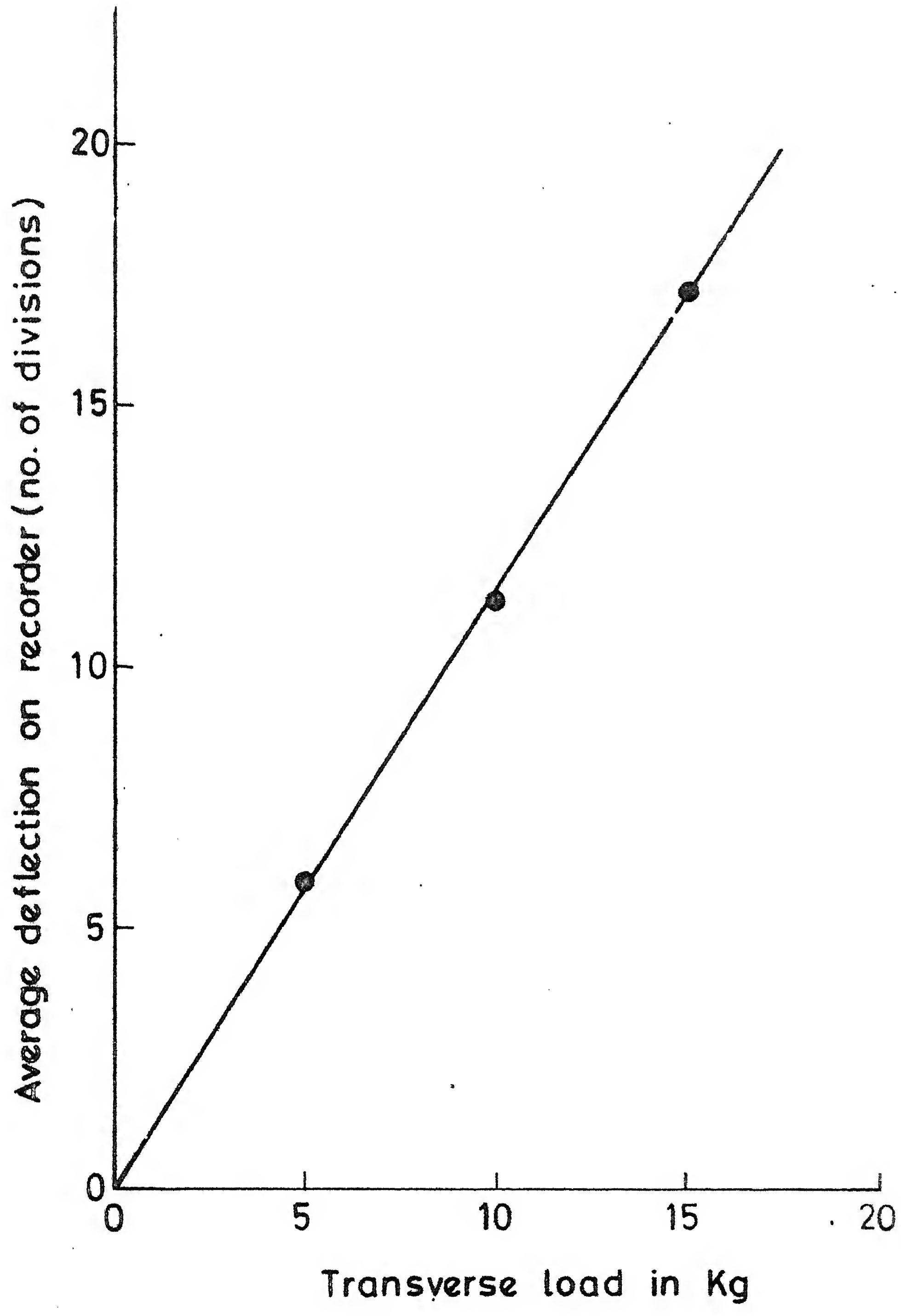


Fig. 11 Static calibration curve for transverse axis

The calibration plots for loading along the vertical, lateral and transverse axes are found to be linear in nature and pass through their respective origins.

Dynamic Calibration:

The procedure adopted was similar to one used for static calibration with the difference that instead of static loads, cyclic loads were applied. Figures 12, 13 and 14 show the calibration plots obtained for vertical, lateral and transverse loading respectively. For the dynamic calibration it was found that all the plots are linear in nature and pass through respective origins.

3.2 TASK DESIGN

Human being still provide major source of input for performing different occupational tasks. Some of the tasks require substantial physical effort. Load lifting is an activity which is frequently indulged into while performing various real life tasks. When the work activity consists of frequent or virtually continuous lifting, energy cost per unit work require careful considerations in order to avoid overstraining of workers. It is with this intention that a repetitive lifting task was selected. The subject was required to lift a known weight from the top level of the force platform to various heights under controlled environmental condition. The task was performed in an environmental chamber whose temperature was controlled at various

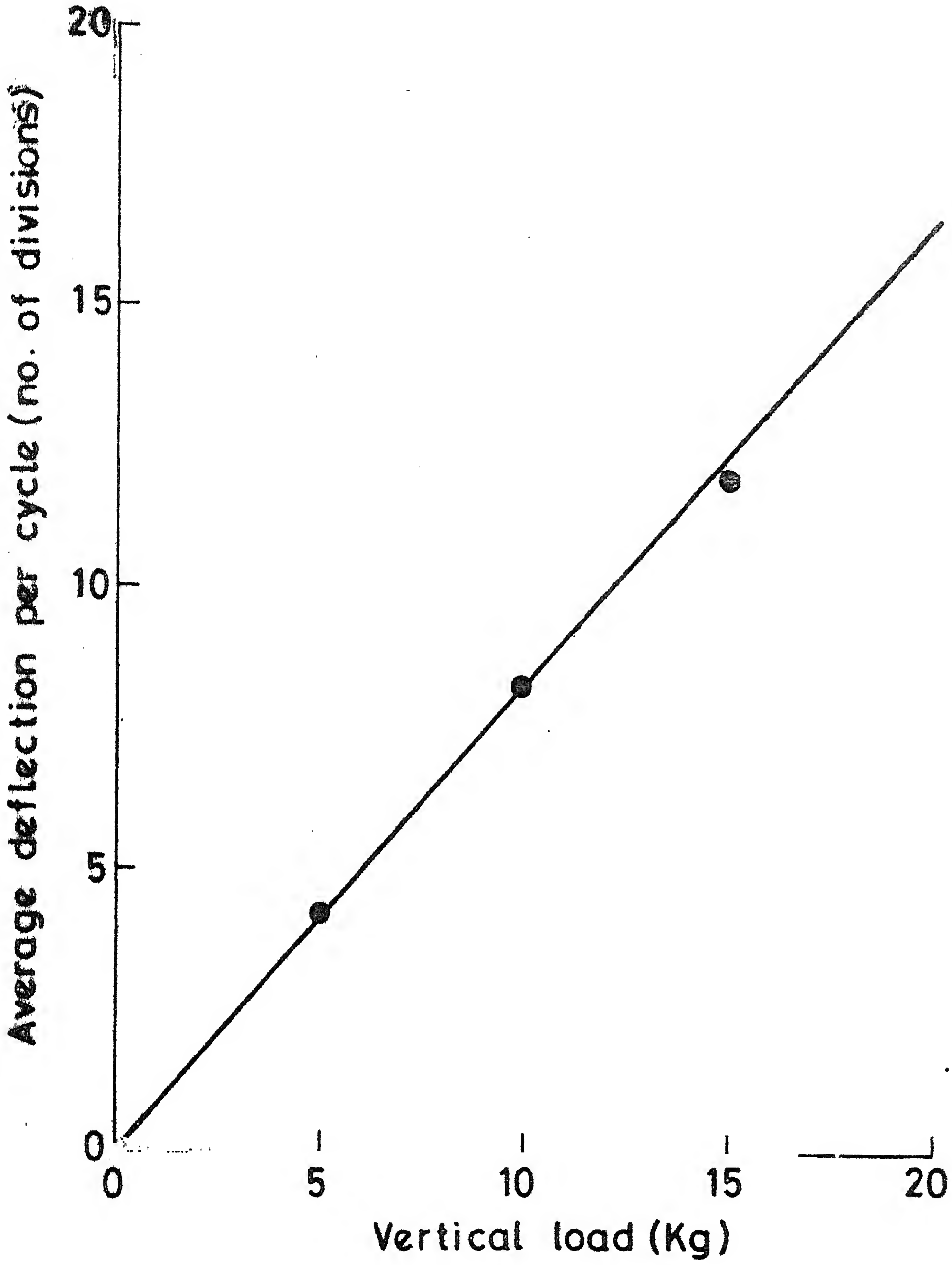


Fig. 12 Dynamic calibration curve for measuring vertical component of reaction

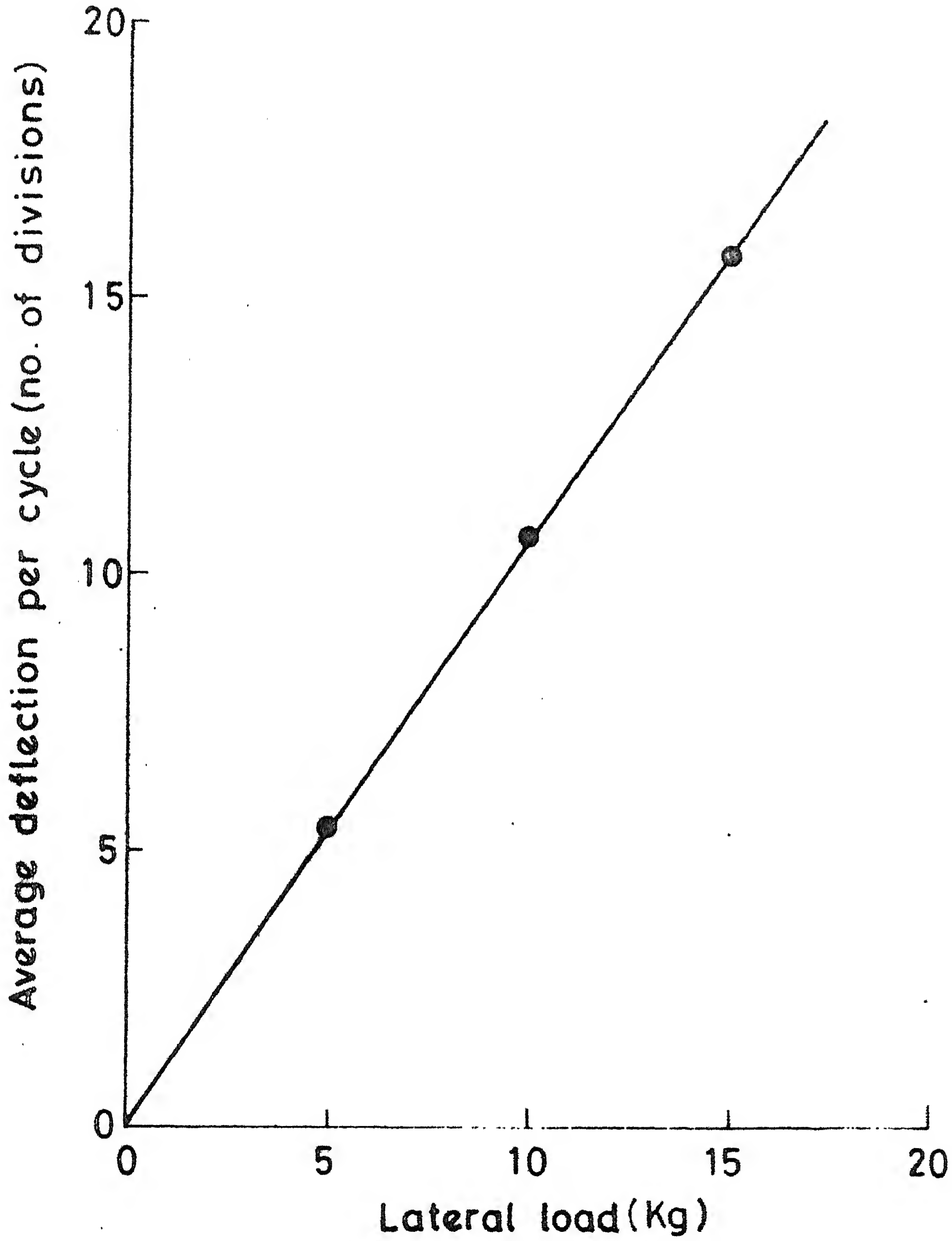


Fig. 13 Dynamic calibration curve for measuring lateral component of reaction

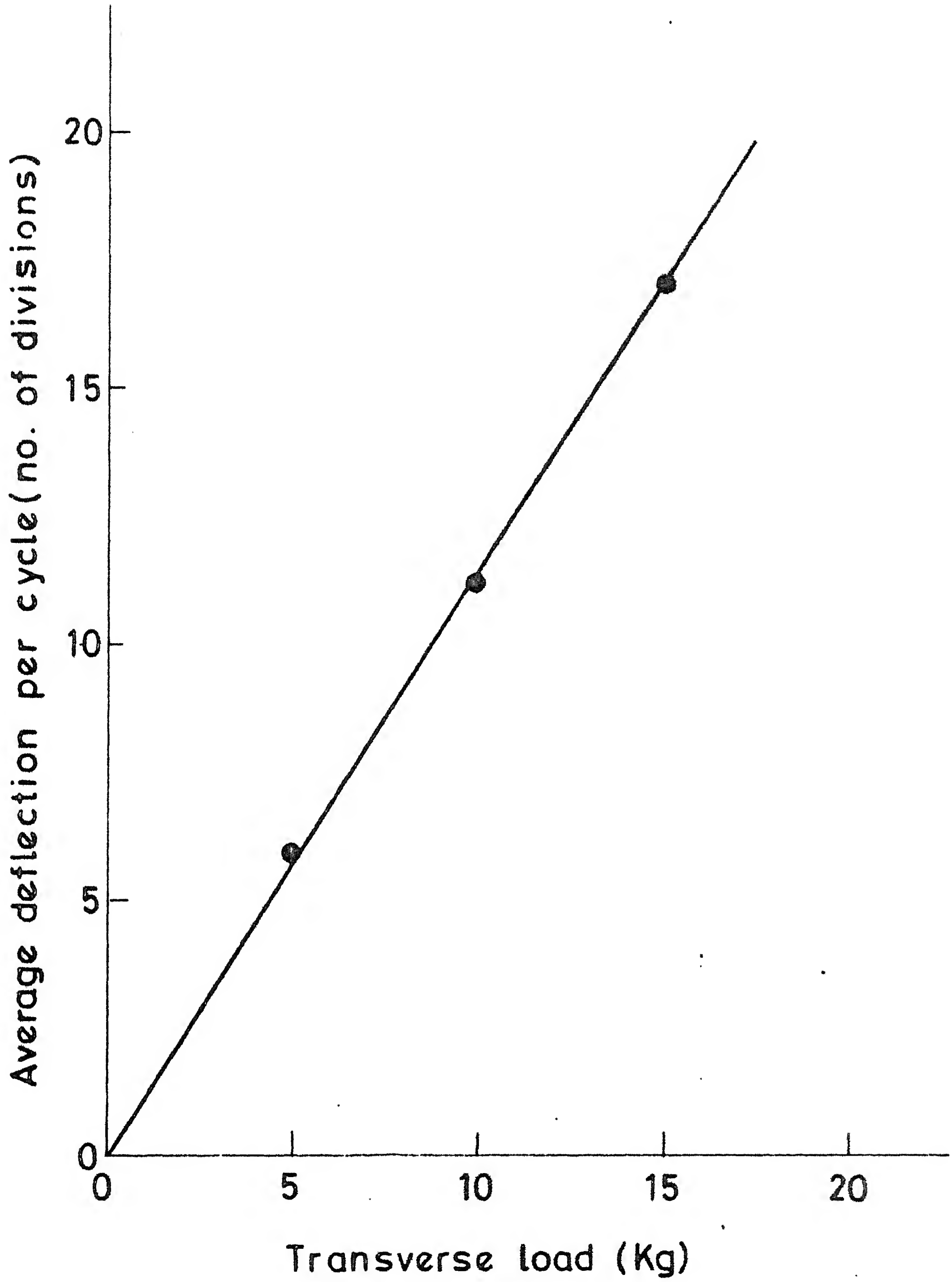


Fig. 14 Dynamic calibration curve for measuring transverse component of reaction

levels. The posture of the subject and horizontal distance between subject and the load to be lifted was fixed. Based on the test runs carried out on the subjects, it was felt that a work pace of 25 cycles per minute is satisfactory. Therefore, the work pace was arbitrarily fixed at this level. Subject was asked to stand erect before and after lifting the load. The load lifted was placed back to original level by another person. The performance of the task places the subject into strenuous physical activity resulting into physiological changes. The physiological changes are measured in terms of heart rate. While performing the task, the subject exerts reactions through feet on the force platform.

3.2.1 Environmental Chamber

Environmental chamber of size 3 m x 3 m x 3 m was erected for the purpose of controlling temperature. An air conditioner of capacity 1.5 tonnes was fitted in the chamber to bring down the temperature at desired levels. Also a strip heater of 2000 Watts was fixed in front of the blower of the A.C unit to raise the temperature above ambient temperature. A thermostat of range 30 ^{o}C - 110 ^{o}C and a relay of 25 amp. were placed in the circuit along with heater to control the temperature at desired levels. Circuit diagram is shown in Fig. 15.

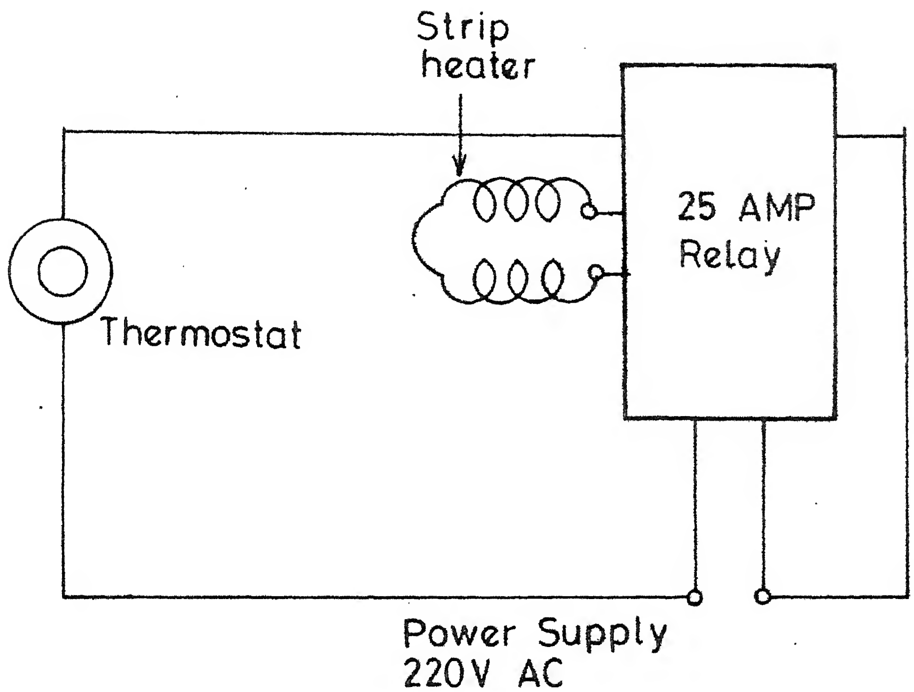


Fig. 15 Circuit arrangement for temperature control during heating

3.2.2 Light and Beep Pacing Device

An audiovisual signalling device was designed and fabricated for giving direction to the subject for paced working.

The signal obtained from frequency generator was fed to a relay which actuated audible as well as visible red-light signal. The signal was given to the subject near the work place. The circuit diagram of the light and beep pacing device is shown in Fig. 16.

3.2.3 Working Table

A working table with the dimensions 0.97 m x 0.37 m x 0.97 m was fabricated using 3 cm x 3 cm x 0.3 cm angle iron. Two wooden planks of 0.95 m x 0.18 m x 0.05 m were used for placement of load as shown in Fig. 17. One of the wooden planks was placed at a height in level with the top of the platform. Provision was made on the working table for placing the second plank at various heights with reference to first plank. The heights selected were 19.0 cm, 28.5 cm, 38.0 cm and 47.5 cm.

3.3 INSTRUMENTATION FOR PERFORMING EXPERIMENTS

As mentioned earlier, the Force Platform translates the three orthogonal components of any induced force into electrical signals. For recording and performing the experiments following devices were used:

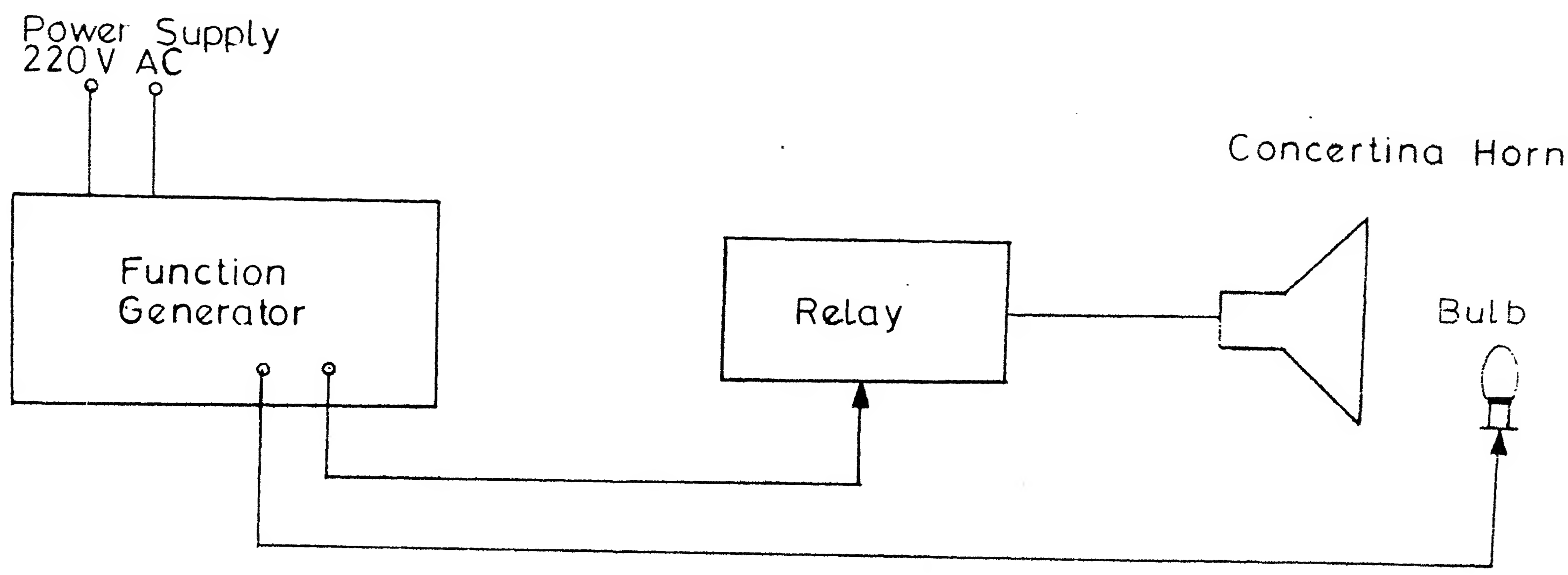


Fig. 16 Line diagram showing circuitry of light & beep signal generating unit

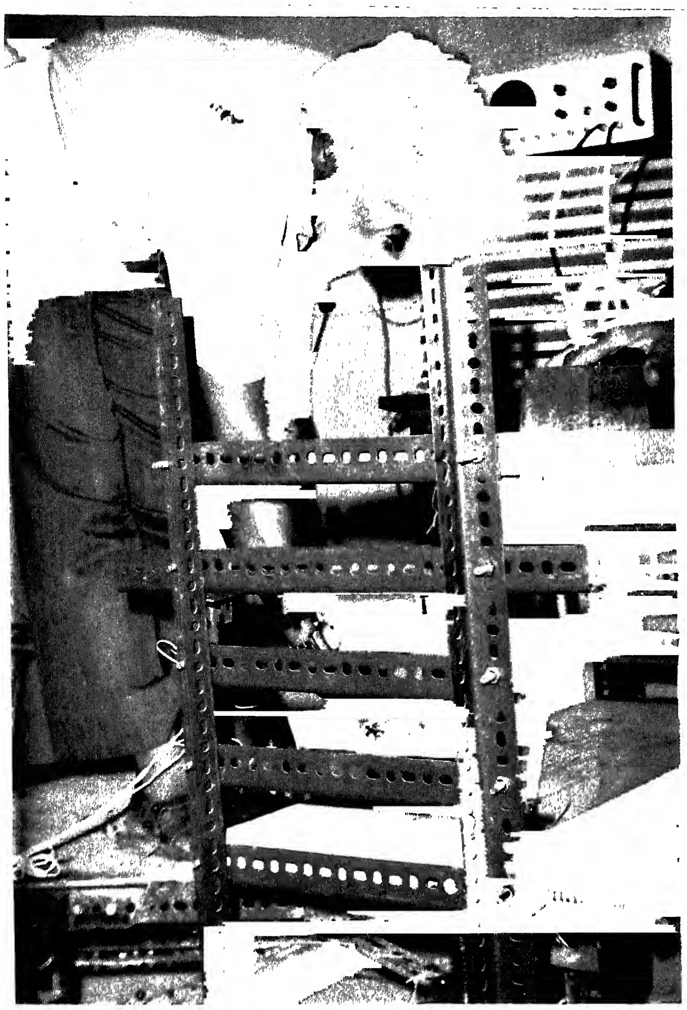


FIG. 17 : A Subject Lifting a Load From One Level to Another Level

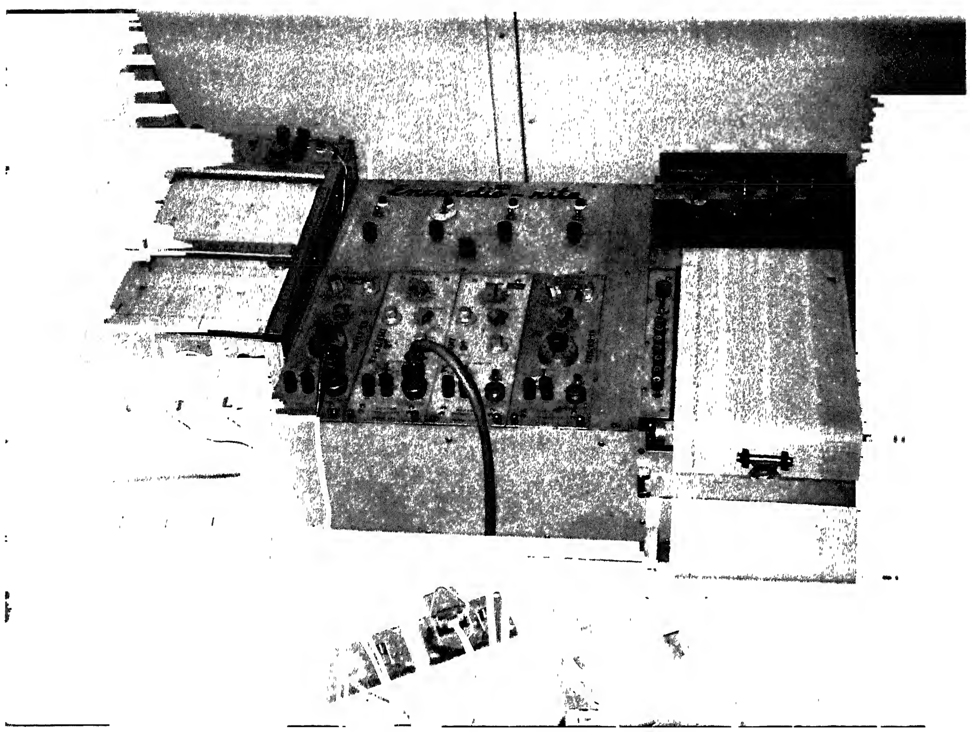


FIG. 18 : Photo showing 4 channel Encardiorite, X-Y Recorder and Bridge Balancing Unit

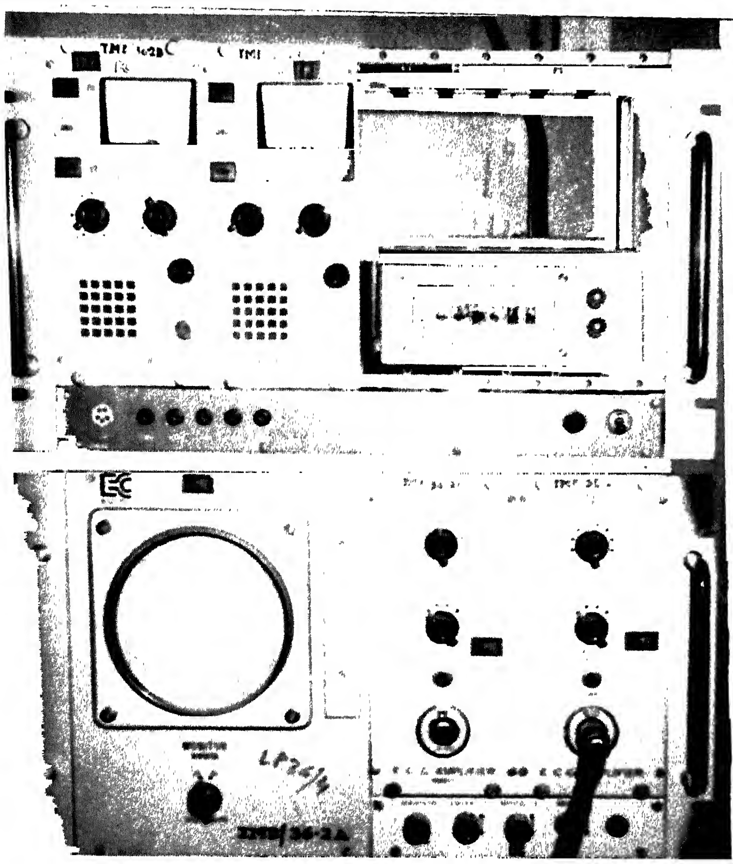


FIG. 19 : Medical Monitoring Device with Heart Rate Meter

3.3.6 Stop-Watch

An ordinary 3 action stop-watch was used to control the duration of exposure time.

3.4 EXPERIMENTAL DESIGN

The various controllable factors for the lifting task under consideration include: load to be lifted, posture, distance between the subject and load, temperature, pace of work, height of lift and exposure time. If we consider a full factorial design with the first five factors at 3 different levels and last two factors at 6 and 4 levels respectively, it can be shown that the total time required for performing the experiment will be enormous. Let us fix the levels of exposure time at 1 min., 2 min., 3 min. and 4. mins. The total experimentation time work out to be 243 hours for one set of readings. From reproducibility considerations if five observations are taken for each experiment, the total number of hours for the complete experiment turn out to be 1215 hours.

From experimental considerations, each time the subject is required to perform the task, his physical condition in terms of heart rate is brought to normal. This means the subject is to be provided with a considerable period of rest before he is called upon to perform the task again. Assuming equal period of work and rest, we will require 2430 hours to complete the experiment on one subject.

Depending upon the number of subjects selected for the experiment, the total time can be estimated. For example with five subjects we will require 20150 hours (approximately 1518 man-days assuming 8-hour work-day) for the experiment.

In view of the enormous amount of experiment time required for the above suggested full factorial design, it was decided to fix 4 factors, namely, weight of the load to be lifted, posture, distance between the subject and the load, pace of work at one predetermined level. In the experimental design finally adopted for the present study 3 levels of temperature, 4 levels of lift height and 4 levels of exposure time were adopted. A summary of the levels of the various factors selected for performing the experiment are given in Table 1.

TABLE 1: Summary of Factors Considered for Experimental Design

Factor	Symbol	Level
Task frequency		i) 25 cycles/minute
Load		i) 5 Kg with right hand
Posture		i) Included angle between feet is 15^{o}
Horizontal distance between the subject and the load		i) 36 cm
Temperature	TMP	i) 20 ^{o}C ii) 30 ^{o}C iii) 40 ^{o}C
Height of lift	LFT	i) 47.5 cm ii) 38.0 cm iii) 28.5 cm iv) 19.0 cm
Exposure time	TM	i) 1 minute ii) 2 minutes iii) 3 minutes iv) 4 minutes

CHAPTER 4

EXPERIMENTAL INVESTIGATION AND INTERPRETATION OF RESULTS

4.1 EXPERIMENTAL PROCEDURE

Four male subjects in the age group of 18 - 25 years, having more or less similar physical characteristics were selected. The subjects were physically fit to participate in the experiment and it was ascertained that they were not suffering from any physical disability. They were briefed about the procedure of experimentation and were given adequate exposure and training for the lifting task in order to ensure consistency in their performance. Trial runs were performed for this purpose.

The physiological changes in the subject due to the performing of the task were measured in terms of heart rate. Electrodes were suitably mounted on the subject for this purpose. The subject was asked to stand centrally on the platform maintaining an angle of 15^{o} between feet. The heart rate was noted in beats per minute. Next, the subject was asked to perform the task maintaining the angle of 15^{o} between feet. A load of 5 kg was lifted by the subject with the right hand from the level of the platform to a certain predetermined height. The task was performed at a set pace for a exposure time controlled with the help of a stop watch.

A predetermined pace of 25 cycles per minute was maintained using the audiovisual device. Initial balancing of the bridge was done under rest condition. While performing the task, the subject exerted forces on the platform through his feet. The reactions were recorded on the recorders simultaneously for all the three orthogonal axes. The deflections obtained were converted into force values using the calibration curves. The resultant body reaction was obtained using the following relationship

$$R_c^2 = R_v^2 + R_l^2 + R_t^2$$

where R_c = Resultant body reaction, kg

R_v = Vertical body reaction, kg

R_l = lateral body reaction, kg

R_t = transverse body reaction, kg.

The heart rate could not be recorded while the subject was performing the tasks. This was due to the jerks and vibrations which affected the body contacts with electrodes. The problem was overcome by providing a normalising time lag after the completion of the task. A time lag of 10 seconds was considered appropriate for taking the heart rate measurements. The increase in heart rate, INC, was determined by finding out the difference in heart rate between pre and post task performance.

The above mentioned procedure was repeated four times for each treatment and the average resultant body

reaction and increase in heart rate was noted down. Further each treatment was repeated for each subject. In all 48 treatments involving 4 levels of lift height, 4 levels of exposure time and 3 levels of temperature were considered.

An attempt was made to classify the selected task into an appropriate category, viz., light, medium, moderately heavy, heavy. The data was collected for this purpose at a lift height of 47.5 cm and temperature of 20 °C for all the four subjects. Average heart rate with exposure time is graphically depicted in Fig. 20.

4.2 ANALYSIS OF DATA AND INTERPRETATION OF RESULTS

Experimental data was analysed to draw certain inferences. A stepwise multiple regression approach was attempted to establish a linear model between increase in heart rate and resultant body reaction, exposure time, lift height, and temperature. SPSS-10 package programme for stepwise multiple regression was used and implemented on DEC-1090 computer. A list of subroutine call codes as well as the results obtained at the last iteration are given in Appendix A. A summary of the results obtained is given in Table 2.

Stepwise multiple regression analysis shows, that simple R for resultant body reaction is 0.74292 with F values of 91.875. This indicates a significant interaction

TABLE 2: Summary of Multiple Regression Analysis Dependent Variable:

Increase in heart rate (beats per minute)

Variable	Multiple R	R Square	Rsq Change	Simple R	B	$\mathcal{B}$	F	Findings $\alpha = 0.05$
R_c	0.74292	0.55193	0.55193	0.74292	14.11072	0.74955	91.875	Significant
TMP	0.74495	0.55495	0.00302	0.25064	0.147009	0.07882	0.903	Not significant
LFT	0.74578	0.55619	0.00124	0.24193	-0.061711	-0.04700	0.305	Not significant
TM	0.74673	0.55761	0.00142	-0.19201	0.502043	0.03976	0.293	Not significant
(Constant)					-28.85218			

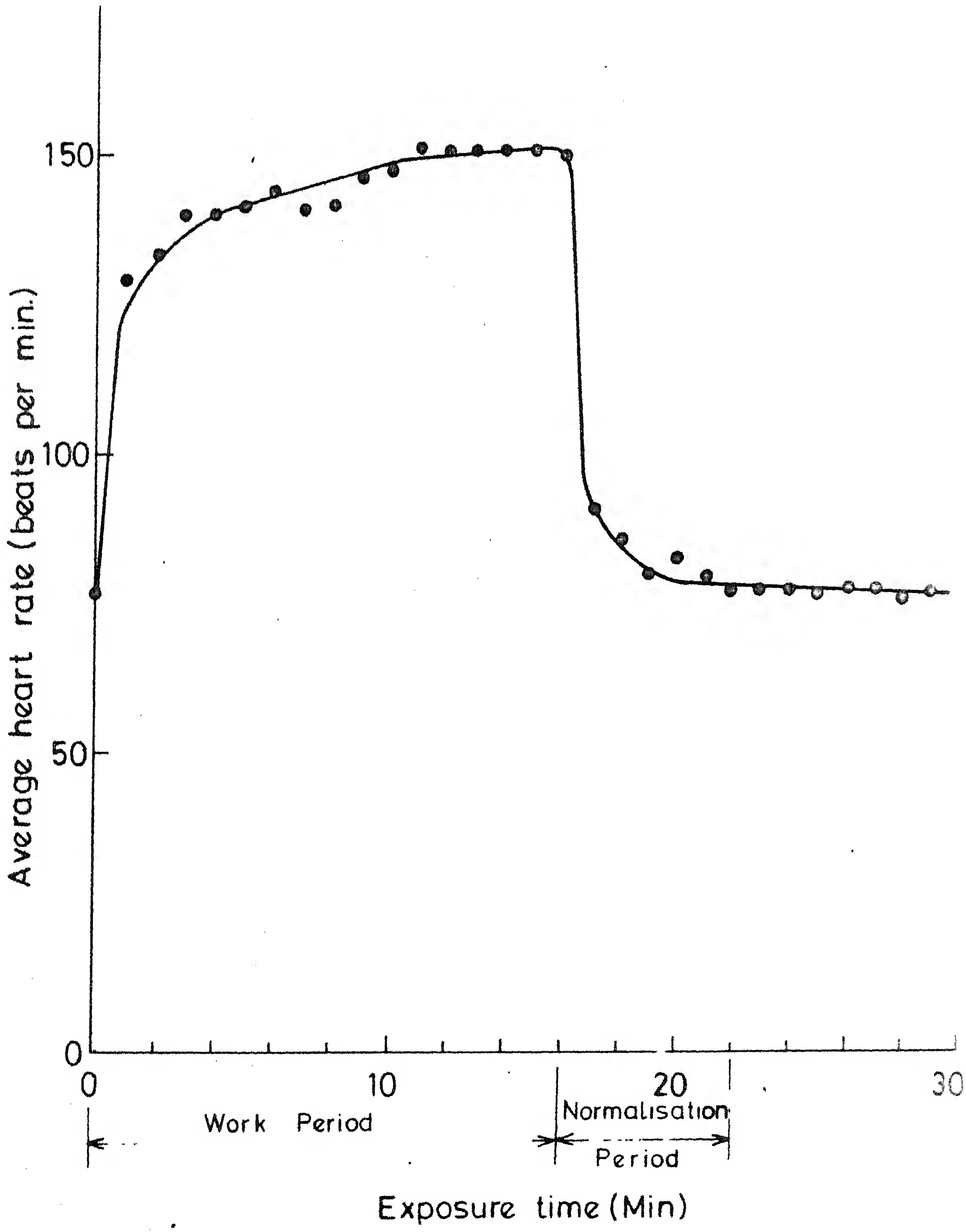


Fig. 20 Average heart rate vs exposure time
Lift height = 47·5 cm , Temperature = 20° C

between increase in heart rate and resultant body reaction. Moreover, it is observed that the interaction between increase in heart rate and resultant body reaction is significant at $\alpha = .05$. No appreciable improvement in multiple R is observed by including temperature, lift height and exposure time in the linear regression equation. The simple R values for temperature, lift height and exposure time are 0.25064, 0.24193, -0.19201 respectively. Further, the F values at $\alpha = 0.05$ suggest that the temperature, lift height exposure do not have significant contribution towards increase in heart rate. The Regression Model has been obtained.

$$INC = -28.85 + 14.11\ RC + 0.147\ TMP - 0.0612\ LFT + 0.5020\ TM$$

The above relationship has multiple R = 0.74673 and F = 28.675 which is significant at $\alpha = .05$. Since individually temperature, lift height and exposure time do not have any significant effect on increase in heart rate, they were deleted from further consideration. The following regression model was obtained for increase in heart rate with resultant bodily reaction.

$$INC = -25.706 + 13.985\ RC$$

For the above model, multiple R value is 0.74292 with F = 115.7901 which is significant at 5% level of significance.

The above analysis establishes the fact that by measuring bodily reactions using Force Platform, it is

possible to predict physiological changes in terms of increase in heart rate.

The analysis also indicates that temperature, lift height and exposure time do not have any statistically significant effect on heart rate change for the lifting task considered. An explanation for this phenomenon was sought through the analysis of the task.

Figure 20 shows the plot of average heart rate vs exposure time, when the task was performed using a lift height of 47.5 cm at 20 °C. It is observed that the heart rate increases with increase in exposure time. From this plot we find that the average rate of energy expenditure is 27.50 kJ/min., which indicates that the task selected is moderately heavy in nature. The calculations for average rate of energy expenditure are given in Appendix B.

Further it is also observed that there is continuous rise in heart rate up to an exposure time of ten minutes and then virtually it stablises at 150 beats per minute. At the end of sixteen minutes of exposure, the subjects were asked to take rest. Virtually the subjects took 6 minutes of rest time for normalizing at initial heart rate level. Thus for the task considered, the work/rest ratio is 2.66 which categorizes the task as moderately heavy [31].

A plausible explanation for the observed phenomenon is that the effect of heavy or moderately heavy

physical task is shown by means of bodily reactions and its manifestation is observed through heart rate change.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 CONCLUSIONS

Based on the statistical inferences drawn in the last chapter, the following conclusions can be drawn within the limits of environmental conditions studied.

1. The physiological cost involved in performing a repetitive load lifting task could be predicted indirectly by using Force Platform. The following simple regression model can be used for finding increase in heart rate by finding resultant body reaction:

   $$INC = -25.706 + 13.985\ RC \qquad \$$$

2. Due to moderately heavy nature of the task, environmental conditions do not have significant effect on increase in heart rate. And the reaction is the dominating stressor for the human subject.

3. The designed Force Platform is rigid and stable. The platform can be used for measuring three dimensional components of the reactions imparted to the platform while performing tasks. The bodily reactions can be used for predicting physiological cost.

$, Where

INC=Increase in heart beat, bpm.

RC=Resultant body reaction

5.2 SUGGESTIONS FOR FUTURE WORK

In the present study the conclusions have been drawn for the selected task based on limited variations. It would be desirable to carry out similar studies with variations to the load to be lifted and the posture used by the subject. It would also be desirable to carry out similar studies on several other physical tasks encountered in real life situation.

The designed and fabricated force platform can be meaningfully utilised for undertaking studies for the following specific purposes:

1. Detection of differences in work methods adopted by individual subjects while performing a given task.
2. The physiological cost involved in operating various types of controls mounted on a panel. This could help in optimal design of control panel.
3. The Force Platform could be used for job evaluation, rating of operators, establishment of fatigue limits and work-rest ratios.

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APPENDIX - A

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The University of Pittsburgh, SPSS-1[illegible], Release 7.01 (24-Nov-77)                1-Jul-82          Page

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TRANSPACE        3[illegible] words                              238 IF/COMPUTE operations

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            VARIABLES LIST    SUBJ,INC,PINC,R1,R2,TM,LFT,RT,IMP,RC,LRC
            INPUT MEDIUM      CARD
            INPUT FORMAT      FREEFIELD
            N OF CASES        [illegible]6
            VAR LABELS        SUBJ SUBJECT CODE/
                              INC  INCREASE [illegible]/
                              PINC  PERCENT INCR. [illegible]/
                              [illegible]  VERTICAL BODY REACTION/
                              [illegible] LATERAL BODY REACTION/
                              [illegible] LIFT HEIGHT [illegible]/
                              [illegible] HEIGHT OF SUBJECT/
                              [illegible] ENVIRONMENTAL TEMPERATURE/
                              [illegible] RESULTANT BODY REACTION/
                              [illegible] LOG OF BODY REACTION TO THE BASE TEN/
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                              REGRESSION=[illegible] WITH I[illegible]C/
                              REGRESSION=[illegible] [illegible],[illegible],T[illegible],RC/

***** REGRESSION problem requires     3[illegible]6 words WORKSPACE, not including residuals *****

            [illegible]
```

Variable(s) entered on step number 4: TM

			Analysis of variance	Df	Sum of squares	Mean square	F
Multiple R	0.74673		Regression	4.	10844.05185	2711.01296	28.67502
R square	0.55761		Residual	91.	8603.38400	94.54268	
Adjusted R square	0.53815						
Standard error	9.72331						

314617

------------------ Variables in the equation ------------------

Variable	B	Beta	Std error B	F
PC	[illegible]	0.74955	1.47211	91.875
[illegible]	0.1470[illegible]	0.07882	0.15472	0.903
[illegible]	-0.6171148D-01	-0.04700	0.11166	0.305
[illegible]	0.5020435D+00	0.03976	0.92819	0.293
(Constant)	-0.2885[illegible]			

------------- Variables not in the equation -------------

Variable	Beta in	Partial	Tolerance	F

Maximum step reached

REGRESSION [illegible] (Creation date = 1-Jul-82) 1-Jul-82 Page 31
File [illegible]

* M U L T I P L E R E G R E S S I O N * * * * * * * * * * * * * * * Variable list 1
Regression list 15

Dependent variable.. [illegible] INCREASE HRT.RT.

Summary table

Variable		Multiple R	R square	Rsq change	Simple R	B	Beta
PC	[illegible]	0.74292	0.55193	0.55193	0.74292	0.1411072D+02	0.74955
[illegible]	[illegible] TEMPERATURE	0.74495	0.55495	0.00302	0.25064	0.1470[illegible]D+00	0.07882
[illegible]	[illegible]	0.74578	0.55619	0.00124	0.23193	-0.6171148D-01	-0.04700
[illegible]		0.74673	0.55761	0.00142	-0.19201	0.5020435D+00	0.03976
(Constant)						-0.2885218D+02	

REGRESSION [illegible] 1-Jul-82 Page 32

CPU time required: 1.51 seconds.

APPENDIX - B

Nature of the Selected Lifting Task

From Fig. 20, we see that heart rate at the end of 1 min. is 124 bpm and at the end of 4 mins. is 140 bpm. For finding out energy expenditure, the relation established by Saha et. al. [23] was used. The relation is as follows:

Heart rate = 2.40 (Energy expenditure in kJ/min) + 66 bpm

Therefore,

$$\text{Energy expenditure in kJ/min} = \frac{\text{Heart rate (bpm)} - 66}{2.4}$$

$$= \frac{124 - 66}{2.4} = 24.167 \text{ kJ/min or } 5.77 \text{ Kcal/min. at the end of 1 minute}$$

and

$$\text{Energy expenditure in kJ/min} = \frac{140 - 66}{2.4} = 30.83 \text{ kJ/min. or } 7.36 \text{ Kcal/min at the end of 4 minutes.}$$

Therefore,

$$\text{Average energy expenditure} = \frac{24.167 + 30.83}{2}$$

$$= 27.5 \text{ kJ/min or } 6.57 \text{ Kcal/min.}$$